THE REPRODUCTIVE BIOLOGY AND MANAGEMENT OF WALLEYE POLLOCK (*GADUS CHALCOGRAMMUS*) IN THE GULF OF ALASKA

By

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Abstract

Ecosystem-based fishery management (EBFM) entails treating resource allocation and management as elements of a comprehensive framework that accounts for ecological linkages. The goal of EBFM is to maintain ecosystem resiliency in a manner that provides for the services desired e.g., fishery catch, species abundance, economic viability. Historically fisheries have been managed on a per species basis with a general focus on increasing or decreasing harvest rates. This management strategy often excludes meaningful processes such as interactions with other species, environmental changes, and economic effects of management changes. One feasible path for implementation of EBFM is through enhancement of existing single-species fishery management models.

Contemporary age-structured stock assessment models generally use an estimate of spawning stock biomass (SSB), i.e., the biomass of female spawning fish, to approximate stock reproductive potential (RP). This approximation inherently assumes a proportional relationship between SSB and RP. Maturity at age or at length is a key aspect of reproductive biology that is central to estimating both RP and SSB. As a sequential augmentation to a single species management model the relationships among body condition, population abundance, the probability of being mature, relative fecundity, and environmental correlates were examined for female walleye pollock *Gadus chalcogrammus* in the Gulf of Alaska.

Maturity data were corrected for spatial sampling bias using a mixed-effects generalized additive model. Once corrected for spatial bias, relationships between maturity, ocean temperature, body condition, ocean productivity (in the form of chlrophyll-*a*), and population abundance were explored. Estimates of fecundity were updated through the processing of archived samples and were also examined with mixed-effects generalized additive models to explore relationships between the previously listed covariates. Multiple measures of RP were examined to explore differences between methods currently incorporated into the stock assessment and updated measures of total egg production and time varying maturity.

Walleye pollock body condition is density-dependent, declining with population abundance. However, after accounting for the effects of length, age, location, year, chlorophyll-*a* concentrations, summer ocean temperature and sample haul, condition has a positive effect on the probability of a fish being mature. Similarly, condition has a positive effect on relative fecundity, after accounting for length, age, egg diameter, chlorophyll-*a* concentrations, winter ocean temperature and sample haul. A positive relationship is observed between depth-integrated summer ocean temperature and maturity and depth-integrated winter ocean temperature and fecundity. Chlorophyll-*a* concentrations have a dome shaped relationship with maturity, peaking at 2.3

mg/m^{-3}, and a negative relationship with fecundity. Variations in body condition have a direct influence on the estimated RP of the fish stock through both differences in the maturation schedule and total egg production. Over some periods these updated estimates of RP differ from estimates of female SSB from the annual stock assessment. Alternative estimates of annual RP, particularly total egg production, may provide better estimates of annual reproductive output than spawning stock biomass. In addition, relationships to density-dependent and density-independent factors provide informative predictions that can be incorporated into stock assessment analyses. Inclusion of spatially explicit information for walleye pollock maturity has implications for understanding stock reproductive biology and thus the setting of sustainable harvest rates used to manage this valuable fishery.

Additionally, because management decisions have economic as well as biological consequences a suite of management strategies were simulated to examine the economic viability of a proposed small-vessel walleye pollock fishery in Alaska state waters in the Gulf of Alaska. As a case-study for straddling stocks, an agent-based model was developed to examine a suite of available federal and state management strategies as they relate to the economic viability of a nascent Alaska state-waters trawl fishery for walleye pollock that may develop after a long history of parallel state and federal waters management. Results of alternative strategies were compared in terms of indicators, such as variance of catch and quasi-rent value. Given the input characteristics of these simulations, the management strategy that produces the best overall improvements relative to status quo involved a federal-waters management strategy that allows for community-based cooperatives and an open access strategy in state-waters. Agent-based models may be used to inform managers of the underlying dynamics of catches and revenues in order to avoid unintended consequences of management decisions and to improve the likelihood of attaining fishery management objectives.

This dissertation provides incremental additions to our knowledge of walleye pollock reproductive biology its spatial and temporal dynamics, and environmental correlates that may serve as ecological indices. These indices, coupled with an improved understanding of the socio-economic examinations of fishery management changes through agent-based modeling, may assist in producing more holistic management strategies, such as EBFM.

Table of Contents

List of Figures

List of Tables

Page

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Chapter 1
Introduction

Ecosystem-based fishery management (EBFM) entails treating resource allocation and management as elements of a comprehensive framework that accounts for ecological linkages (Larkin, 1996; Link, 2002). One feasible path for implementation of EBFM is through a sequential augmentation of existing single-species fishery management models (Goodman et al., 2002; Pikitch et al., 2004; Pitcher et al., 2009) with the goal of maintaining ecosystem resiliency in a manner that provides desired services. These services may be biological, social, or economic. For instance, there is a desire to maintain fish populations at levels that provide for consistent targeted fisheries removals, afford opportunities for cultural harvest, support commercial ventures, or maintain a prey base for other ecosystem components.

A fish population's reproductive biology is of particular significance to fishery managers because contemporary age-structured assessment models generally use an estimate of spawning stock biomass (SSB), i.e., the biomass of female spawning fish, to approximate stock reproductive potential (RP). Inherent in these models is the assumption that SSB is proportional to total egg production, one measure of RP, the total number of eggs released annually by a stock (Lambert, 2008; Marshall, 2009). However, this measure of RP may be influenced by the demographics of the population, the environment, fishing effects, and prey availability and the relationship may not be proportional (Barneche et al., 2018). Examinations of the reproductive biology of fish populations may provide meaningful insight for both single-stock management and provide a valuable understanding of a species' life history that may result in more effective EBFM.

Another component of EBFM is to manage fisheries in a socio-economic context. For example, what are the trade-offs associated with different management scenarios for fishery resources that straddle jurisdictional boundaries? Can strategies be identified, before implementation, that can achieve intended biological, social, and economic goals? Simulation modeling provides one avenue for exploring alternative management scenarios and is a tool that policymakers can utilize to help make informed management decisions.

This thesis is designed to address a number of these items as they pertain to stock assessment and fishery management of walleye pollock (*Gadus chalcogrammus*; hereafter pollock) in the Gulf of Alaska (GOA). Pollock are considered one stock throughout the GOA with the fishery managed by applying a harvest rate to an assessment model estimate of SSB. The SSB is based in part on an estimate of the maturation schedule, the proportion of female fish that are mature at a given age. For the annual stock assessment, maturity estimates for the GOA are taken as the average of maturity rates from 1983 through the most recent winter assessment (Dorn et al., 2013). This annual maturity rate was evaluated for spatial pattern and dynamics in Chapter 2. Estimates of fecundity, the number of eggs that a female pollock releases during a given year, are currently not incorporated directly into the stock assessment. SSB is used as a surrogate for fecundity-at-age to calculate mean generation time of the GOA pollock stock (Dorn et al., 2013).

The assumption that SSB and RP are proportional is critical because SSB is used for status determinations and to implement the allowable biological catch (ABC) and overfishing (OFL) control rules (Dorn et al., 2013). Furthermore, because the ABC control rule used by the North Pacific Fishery Management Council (NPFMC) to manage the stock requires that fishing mortality be reduced linearly below an inflection point ($B_{40\%}$ the biomass corresponding to 40% of the unfished stock level when fishing at $F_{40\%}$), yield can be highly dependent on spawning biomass.

Interannual variability of pollock maturity has been observed in the eastern Bering Sea (Stahl and Kruse, 2008) that may lead to a higher contribution toward SSB by younger fish than is currently modeled (Ianelli et al., 2010). Similarly, fecundity can vary with fish length and condition, the quality and availability of food resources, environmental conditions (e.g., temperature) and as a response to stock biomass and fishing pressure (Lambert, 2008). There has been no robust analysis of potential spatiotemporal variability for GOA walleye pollock maturity or fecundity to date.

Examinations of variations in fecundity in lieu of SSB of other gadoids, such as Atlantic cod *Gadus morhua*, showed different responses to reductions in stock size, e.g., fecundity was not proportional to SSB during all time periods (Marshall, 2009). Spencer and Dorn (2013) used simulation modeling of the GOA pollock stock assessment to show how reproductive dynamics affect stock productivity. They found that the effect of applying weight-specific relative fecundity (i.e., increasing fecundity per unit mass with increasing body weight) was to raise the estimate of the fishing mortality rate at maximum sustainable yield relative to an estimate using SSB as reproductive potential. This resulted from a higher level of stock productivity being associated with a greater reproductive output (relative to an unfished stock) with positive weight-specific fecundity.

The pollock stock assessment for the GOA may be improved by incorporating contemporary fecundity and maturity estimates under current stock levels and climate regimes. Moreover, given that phenotypic plasticity in fecundity and maturity of other gadoids is related to factors, such as stock density (Rijnsdorp et al., 1991; Marshall, 2009) and temperature and prey availability (Kjesbu et al., 1998), the pollock stock assessment may be further improved by estimating functional relationships between temporal and spatial variability in fecundity and maturity under different stock abundance and environmental conditions. Environmental factors, such as temperature and indices of ocean productivity, regulate most physiological processes and govern the amount of energy available for winter spawning. Quantifying these functional relationships may allow fecundity and maturity to be treated dynamically in future stock assessments and management strategy evaluations. Chapter 3 examines relations in maturity and fecundity with environmental indices and population abundance to explore variability between several estimates of reproductive potential.

The NPFMC continues to explore the possibility of a catch share program for the GOA pollock fishing fleet as a bycatch reduction measure. One issue that has been raised with a catch-share program for the fleet is the economic impact it would have on GOA fishing communities. In recent years, about 67% of GOA pollock are delivered to processors in Kodiak, Alaska, with 32% of landings being delivered to Sand Point, Dutch Harbor, King Cove, and Akutan, and 1% of the catch is distributed to numerous other small fishing ports (Dorn et al., 2013). Because pollock are distributed across a jurisdictional boundary (state and federal waters), some management options available to the federal managers may not be available to state managers for legal, social, or political reasons. In Chapter 4, an agent-based model (Gilbert, 2008) was used to explore the implications of different management strategies between governing bodies.

By improving conceptual understanding of state and federal management strategies, this model will provide managers with information for determining optimal management strategies as they relate to fishery economics at the port level. Further, it could result in informing strategic decisions that are linked to policy decisions. This model is set up as a discrete, static, stochastic simulation-optimization framework to estimate the local economic impacts of combinations of federal and state management strategies. The output of the simulated economic outcomes was compared across stock levels consistent with recent (1998-2015) fishery history.

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Chapter 2

Interannual and spatial variability in maturity of walleye pollock *Gadus chalcogrammus* and implications for spawning stock biomass estimates in the Gulf of Alaska[I]

2.1 Abstract

Catch quotas for walleye pollock *Gadus chalcogrammus*, the dominant species in the groundfish fishery off Alaska, are set by applying harvest control rules to annual estimates of spawning stock biomass (SSB) from age-structured stock assessments. Adult walleye pollock abundance and maturity status have been monitored in early spring in Shelikof Strait in the Gulf of Alaska for almost three decades. The sampling strategy for maturity status is largely characterized as targeted, albeit opportunistic, sampling of trawl tows made during hydroacoustic surveys. Trawl sampling during pre-spawning biomass surveys, which do not adequately account for spatial patterns in the distribution of immature and mature fish, can bias estimated maturity ogives from which SSB is calculated. Utilizing these maturity data, we developed mixed-effects generalized additive models to examine spatial and temporal patterns in walleye pollock maturity and the influence of these patterns on estimates of SSB. Current stock assessment practice is to estimate SSB as the product of annual estimates of numbers at age, weight at age, and mean maturity at age for 1983-present. In practice, we found this strategy to be conservative for a time period from 2003-2013 as, on average, it underestimates SSB by a 4.7 to 11.9% difference when compared to our estimates of SSB that account for spatial structure or both temporal and spatial structure. Inclusion of spatially explicit information for walleye pollock maturity has implications for understanding stock reproductive biology and thus the setting of sustainable harvest rates used to manage this valuable fishery.

2.2 Introduction

Ontogenesis and phenology are unique for a particular fish stock and often vary over time due to ecological and fishery effects. Gaining comprehensive knowledge about stock life history parameters (e.g., fecundity, maturity, age-structure) is expensive; therefore, fishery scientists endeavor to acquire as much information as possible during fishery-independent surveys to inform stock assessment models. However, the sampling methods chosen to characterize a stock, while perhaps maximizing the quantity of data obtained, may affect precision and accuracy of population statistics, leading to a biased view of the true status of a stock. Although some of these biases, such as gear selectivity, can be addressed by parameter estimation within stock assessment mod-

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els, other biases, such as misspecified maturity ogives, require independent estimation by field studies (Hilborn and Walters, 1992; Farley et al., 2014).

Marine fisheries management is often based on biological reference points (e.g., harvest rates or biomass levels) that specify the framework for sustainable harvest levels. These reference points are predicated on an assumed relationship between stock reproductive potential (RP) and subsequent recruitment. Contemporary age-structured assessment models generally use an estimate of spawning stock biomass (SSB), i.e., the biomass of female spawning fish, to approximate stock RP. This approximation inherently assumes a proportional relationship between SSB and RP (Lambert, 2008; Marshall, 2009). Maturity at age or length is a key aspect of reproductive biology that is central to estimating both RP and SSB. Bias in stock parameters defining maturity ogives can lead to fishery management decisions based on misspecified biological reference points. Additionally, these parameters may vary with fish density or environmental conditions. Functional relationships are often elusive, hindering our ability to properly incorporate population dynamics into stock assessments, including forecasts of stock responses to alternative management strategies.

Walleye pollock *Gadus chalcogrammus* (hereafter, pollock) is a moderately long-lived species (maximum age of 22 yr) that is widely dispersed throughout the North Pacific Ocean (Mecklenburg et al., 2002). The pollock fishery off Alaska is the largest fishery in North America, on the order of 1.3 million metric tons worth $343 million in exvessel revenue annually (NMFS, 2014). The volume of pollock harvested in the eastern Bering Sea fishery is an order of magnitude larger than that of the Gulf of Alaska (GOA). Nevertheless pollock comprises the largest portion of the groundfish catch (41% in 2013) by weight in the GOA (Fissel et al., 2014). There is some evidence that pollock spawning populations in the northern portion of the GOA are genetically distinct from pollock in Shelikof Strait (Olsen et al., 2002), however uncertainty remains and pollock are managed with a statistical age-structured assessment model as a single stock in the central and western GOA (Dorn et al., 2010, 2012). Maturity is incorporated into the stock assessment as the average maturity at age for the time period of 1983 to present, and does not attempt to track temporal variability or spatial trends in maturity (Dorn et al., 2013).

Length at 50% maturity (L_{50}) for eastern Bering Sea pollock appears to be related to length at age, and there is some evidence for a density-dependent relationship between L_{50} and stock biomass (Stahl and Kruse, 2008a). In other species, maturity or total egg production can vary in relation to fish length and condition (Marshall et al., 1998; Rideout et al., 2000; Marshall, 2009), the quality and availability of food resources, environmental conditions (e.g., temperature), and as a response to changes in stock biomass and fishing pressure (Trippel, 1999; Lambert, 2008). Spatial variability in GOA pollock maturity and potential relationships with these density-dependent and -independent factors are unknown, and temporal variability has been infrequently examined. Pol-

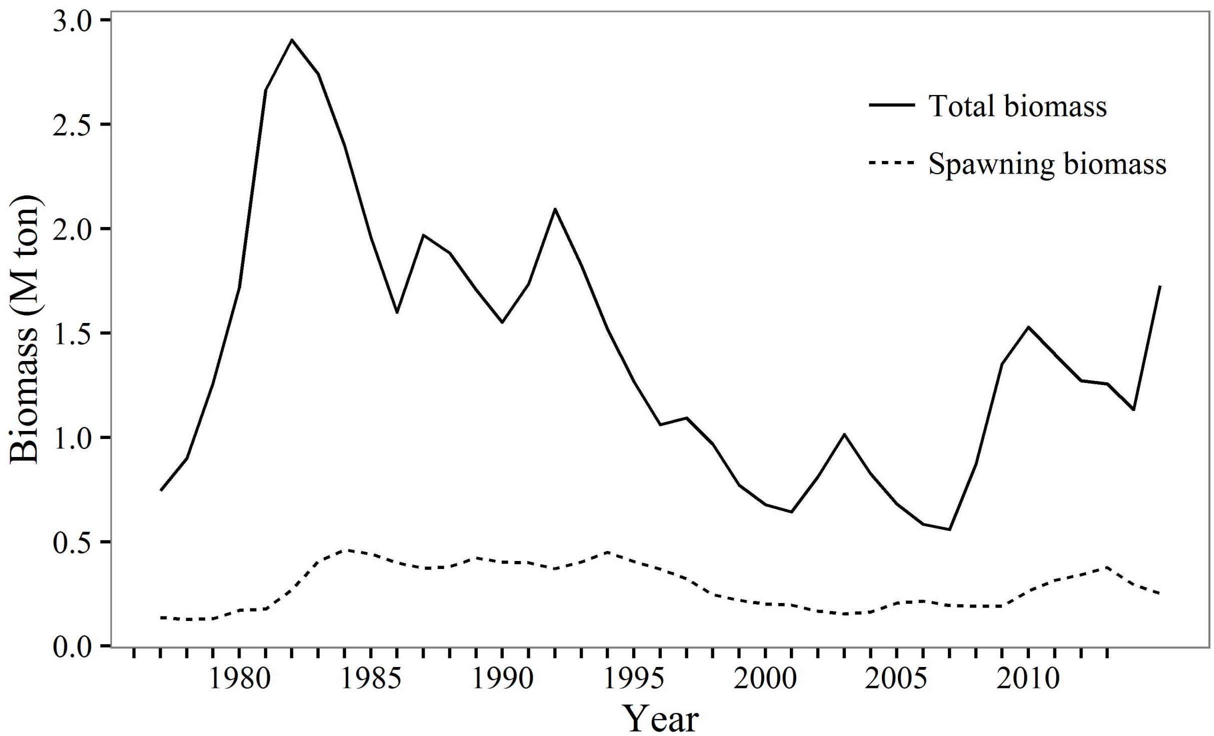

Figure 2.1. Estimates of age 3+ total biomass (dashed line) and spawning stock biomass (solid line) of walleye pollock in the Gulf of Alaska (from Dorn et al. 2013).

lock growth and GOA stock biomass are inversely related (Fig. **??**) and weight-at-age has increased dramatically over 2000-2013, particularly for female pollock older than age-4 (Fig. **??**). However this relationship is less clear over 2007-2013, when the population numbers have increased and weight at age has remained high. Additionally, the GOA experiences significant environmental variability, including periodic climate regime shifts (Hare and Mantua, 2000). There are many potential effects of varying temperatures on pollock; for example, cool conditions appear to be associated with improved reproductive success and increase the abundance of the euphausiid *Thysanoessa* spp., an important prey of pollock(Pinchuk et al., 2008). Changes in individual pollock growth rates, perhaps associated with shifts in pollock biomass and environmentally driven changes in prey, may influence maturation rates and distribution of mature pollock in the GOA.

Trawl catches collected during annual Alaska Fisheries Science Center (AFSC) hydroacoustic surveys NMFS (2013) provide samples to assess maturity of pollock in the GOA. The acoustic surveys were conducted along transects in Shelikof Strait, near Kodiak Island, Alaska, typically in March each year to estimate pollock biomass by location. Periodic trawl tows were utilized to examine the age and size structure of pollock schools observed via acoustics and to determine the species compositions NMFS (2013). Pollock were also sampled from these tows for maturity

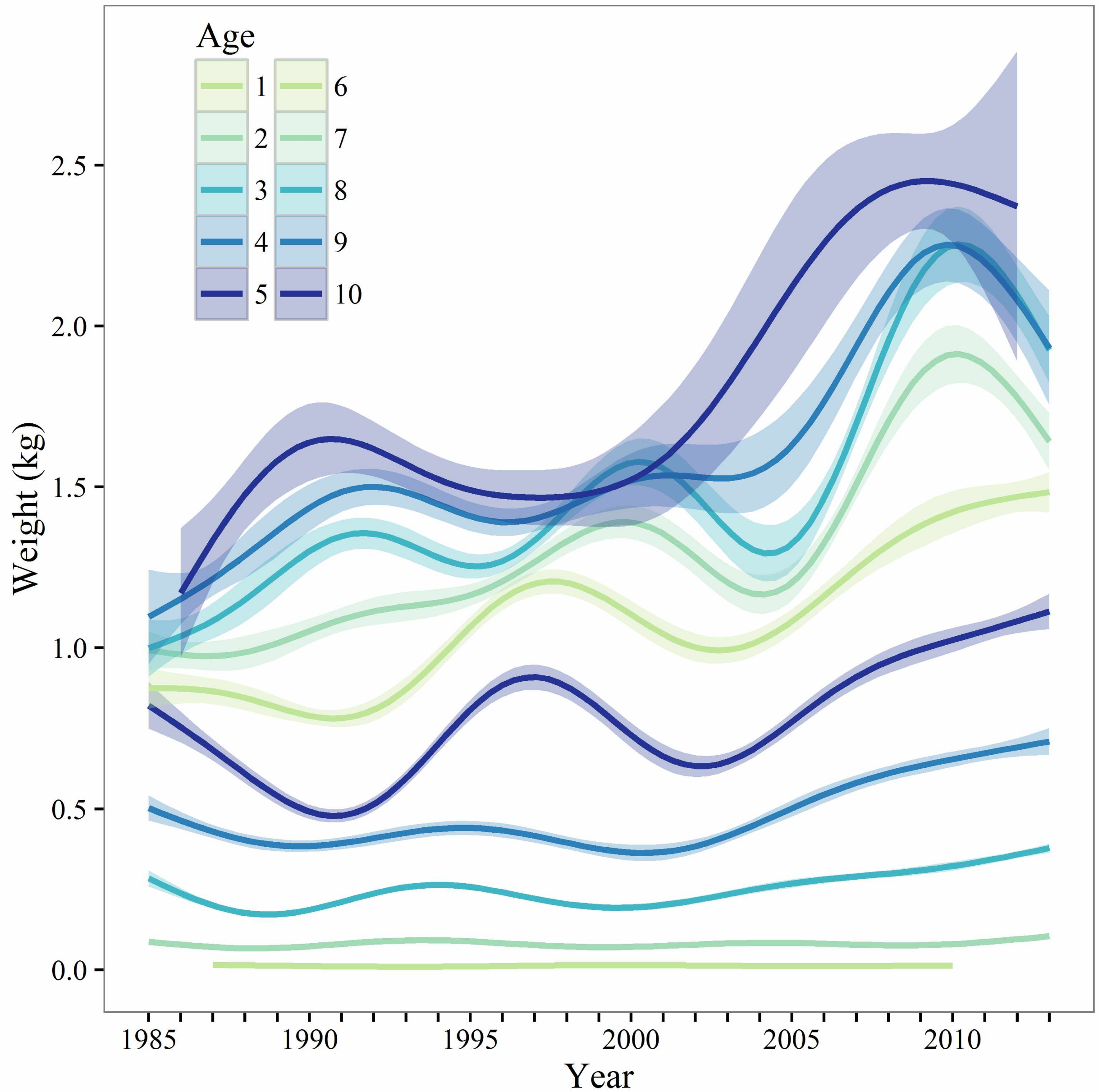

Figure 2.2. Female walleye pollock weight at age for ages 1-10 from fishery-independent samples in Shelikof Strait, Gulf of Alaska. Solid lines are generalized additive model estimates; shaded areas are 95% confidence intervals.

assessment, although sample sizes were not scaled to localized biomass. Macroscopic maturity estimates were determined using a 5-stage key Stahl and Kruse (2008b) or an 8-stage key from 1996-2007 Williams (2007). Maturity ogives were calculated from all samples during a given survey without regard to spatial variability. Ideally, to be representative, a maturity ogive for a population should be based on samples weighted by the relative biomass across the full geographic distribution of the stock Farley et al. (2014).

The goal of our study was to identify annual and spatial patterns in GOA pollock maturity based on samples collected during NMFS acoustic surveys in Shelikof Strait during 1983-2013. In particular, we examined spatial bias in the estimation of a pollock maturity ogives and the influence of observed bias on estimates of SSB. While the pollock population is dispersed throughout the GOA, we chose Shelikof Strait only, as it contains the largest spawning concentration of pollock in the GOA, and it has been the most consistently sampled during annual assessment surveys Dorn et al. (2013).

2.3 Materials and Methods

We analyzed data on gonad maturity of female pollock collected during annual acoustic surveys conducted by NMFS in the western GOA in February-March from 1983 through 2013. Maturity was estimated macroscopically using a 5-stage key developed for pollock Stahl and Kruse (2008b). This key was expanded into an 8-stage key in 1996 that was in use until 2007 Williams (2007), after which the 5-stage key was again employed. For our study, the maturity keys were reduced to a two-stage scale (mature/immature) with fish in pre-spawning, spawning, and spent stages classified as mature and fish in immature and developing stages classified as immature. Fork lengths (FL) were rounded to the nearest cm for each sampled fish and ages were determined by the AFSC Age and Growth Program Matta and Kimura (2012). Fish of age-10 and greater were binned as a plus group. Our analyses were restricted to pollock sampled from Shelikof Strait and to the southwest toward 55°30′ N, 157°W, west of Chirikof Island, as it is the region in the GOA with the most continuous sampling for pollock abundance and maturity (Fig 2.3) No maturity samples are available for 1999 and 2011 because surveys were not conducted in those years (Table 2.1). A total of 17,236 fish were available for age-based modeling and 34,342 fish for length-based modeling (Table 2.1). Associated length information was available for all fish that were aged, therefore the data used for age-based modeling was also used as an "equivalent dataset" for examining the explanatory power of age- and length-based models.

Maturity M was modeled as a binomial response with a logit link using generalized additive models (GAMs) for the full 1983-2013 dataset to examine spatial and temporal variability. Ex-

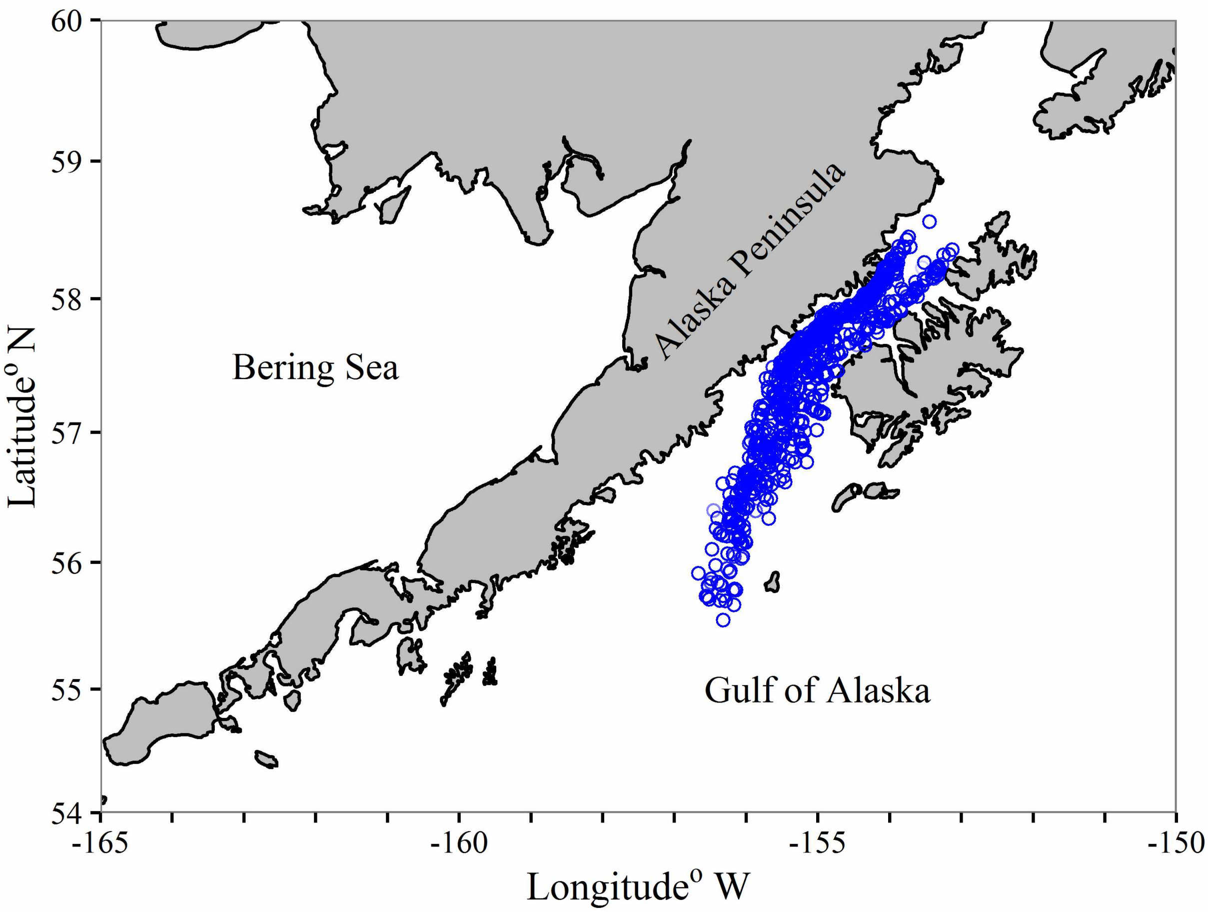

Figure 2.3. Sample locations of walleye pollock used for maturity assessment over 1983-2013 in Shelikof Strait, Gulf of Alaska.

Table 2.1. Annual maturity sample sizes collected by length and age for walleye pollock in Shelikof Strait for 1983 to 2013.

Year	Length	Age	Year	Length	Age
1983	2,394	1,103	1998	1,282	784
1984	2,889	1,467	2000	1,294	363
1985	2,091	1,183	2001	1,399	378
1986	1,178	618	2002	667	326
1987	733	643	2003	775	321
1988	949	464	2004	712	440
1989	1,102	545	2005	483	335
1990	1,740	1,117	2006	691	487
1991	675	567	2007	453	320
1992	1,161	765	2008	426	248
1993	1,365	624	2009	430	301
1994	2,940	632	2010	462	244
1995	1,243	575	2012	523	372
1996	2,198	775	2013	530	386
1997	1,547	853			
Sum	34,332	17,236			

planatory variables included year, latitude, longitude and either age or length. The full GAM has form:

$$M = f_1(Age) + f_2(Longitude, Latitude) + f_3(Haul, bs = re) + Year + \varepsilon, \tag{2.1}$$

where the f's are functions. To limit the analysis to biologically reasonable relationships the number of knots k or maximum degrees of freedom for the smoothing term applied to age or length, was restricted to 4 (Clarke et al., 2003; Peterson et al., 2014). Year was modeled as a categorical variable. Multiple maturity samples were collected from a given trawl haul *Haul* violating assumptions of independence; therefore, *Haul* was included as a random effect using the *bs=re* statement. All models were evaluated with the mgcv package in R version 3.1.2 (R Core Team, 2017; Wood, 2011). Final parameter estimates were calculated using restricted maximum likelihood. The relative explanatory power of predicting maturity by length or age, as well as reduced models, was examined using the Akaike Information Criterion (Akaike, 1973; Burnham and Anderson, 2002). Comparisons between age- and length-based models were estimated on an equivalent dataset. Normal approximate standard errors were estimated in the mgcv package (Wood, 2011) on the predictor scale and transformed to the response scale.

Estimates of pollock biomass at length for 0.5 nmi transect segments (Provided by T. Honkalehto, NMFS, Seattle, pers. comm.) were used as prior weights on maturity data to generate a biomass-weighted maturity curve (Farley et al., 2014) These biomass estimates were calculated by combining acoustic backscatter information along transects with size-composition data from associated trawl samples (Honkalehto et al., 2008). Although acoustic biomass estimates are produced for the continuous survey transects, samples for maturity estimation are from individual haul locations. Therefore, direct weighting cannot be applied due to the differing spatial extent of the two datasets. Instead, a classification and regression tree (CART) model (Loh, 2011; R Core Team, 2017; Therneau et al., 2014) was implemented to identify regions with similar maturities over which pollock biomass could be summed.

Classification and regression trees are machine-learning procedures that recursively partition the data space based upon the ability of explanatory variables to predict the response variable (De'ath and Fabricus, 2000). In our application, the CART model provides regions *Region* with similar probabilities of a female fish being mature using the following model structure:

$$M_{Region} = Longitude + Latitude. \tag{2.2}$$

The CART model was constrained by a complexity parameter set to 0.01 that defined a level of model fit below which models were dropped via 10 fold cross-validation (Therneau et al., 2014).

Prior weights for the maturity data were calculated by binning transect biomass data into 5 cm length increments (length group) by year and region. Estimates of transect biomass were assumed to be split 50:50 among males and females. Transect biomass estimates were length-structured rather than age-structured, however estimates of maturity by age are necessary for incorporation into an age-structured stock assessment. Therefore predicted age distributions by length group, region, and year were assigned using a conversion matrix (i.e., length-age key). This conversion matrix allows for a proportional allocation of ages to the spatial transect data through the designation of biomass at age for each region. Comparisons using biomass as prior weights were restricted to years with available data, i.e., 2003 through 2013 (excluding 2011). The reciprocal values of summed biomass by age, length group, year and region were used as prior weights in the top GAM models previously chosen using the AIC.

To generate comparable estimates for examining the influence of annual and spatial variability, maturity estimates for Shelikof Strait were also calculated via a generalized linear model (GLM; R Core Team, 2017), which is the method utilized in the stock assessment (Dorn et al., 2013). This estimate of maturity (base model) was used for comparison to the GAMs that explicitly incorporate spatial variability (spatial model) and the biomass-weighted spatial model (weighted spatial model). Graphical comparisons of averaged estimates from these models include 95% bootstrapped confidence limits (Wickham, 2009). The median size and age at maturity (L_{50} and A_{50}, respectively) were estimated for each model with confidence limits calculated as two times the model-generated standard error.

Annual estimates of the numbers of pollock at age were obtained from the GOA age-structured stock assessment in Dorn et al. (2013, Table 1.17). These estimates were generated via an age-structured stock assessment developed using AD Model Builder (Fournier et al., 2012) that incorporates both fishery dependent and independent data sources such as fishery age and length catch compositions and NMFS trawl survey age and length catch compositions (Dorn et al., 2013). Annual pollock weight at age used in the stock assessment to calculate spawning biomass is based on Shelikof Strait survey data, and is considered to represent weights at time of spawning (Dorn et al., 2013). Female spawning stock biomass was calculated for a given year i as:

$$SSB_i = \sum W_{a,i} * M_a * N_{a,i}, \tag{2.3}$$

where $W_{a,i}$ is the mean fish weight at age a in year i, M_a is the average proportion of mature females (provided by the base, spatial, or weighted spatial models) at age, and $N_{a,i}$ is the number of fish of a given age in year i from the stock assessment (Dorn et al., 2013). Prediction intervals for SSB were estimated as two times the maturity model(s) estimated standard errors.

Results

The inclusion of sample location improved model fits when compared to the base model (Table 2.2) for both length-based and age-based models. Variants of the global age or length models with terms removed were not considered an improvement because their AIC model weights were less than 1%, therefore they were excluded from further consideration (Table 2.2). Maturity at length was found to be a better descriptor of pollock maturity than maturity at age (Table 2.3), when compared using an equivalent dataset.

Our analyses reveal a spatial pattern in the proportion of pollock mature at age or length in Shelikof Strait. The pattern is manifested as a gradient with a high proportion (>0.5) mature along the coast of the Alaska Peninsula to the northeast, and a low proportion mature (<0.4) to the southwest. A CART model divided the data space into five partitions explaining the geographic pattern in proportion mature. However, the CART model is constrained by a grid structure based on latitude and longitude, and produces breaks on a northeast-southwest diagonal within Shelikof

Table 2.2. Age- and length-based model fits with AIC values and AIC weights. Note that the age-based models were estimated on a reduced dataset and are not directly comparable to length-based models. The base model is identified with *, the spatial model (unweighted and weighted) is identified with †. Models are ranked from best to worst fitting. Where *age* = is the numeric fish age, *length* = individual fish length, *lon* = longitude in decimal degrees, *lat* = latitude in decimal degrees, *year* = the year sampling occurred as a factor, *haul* = individual hauls that samples originated from, incorporated as random effects, *(e)df* = model estimated degrees of freedom, AIC = Akaike information criterion, Δ_i = AIC difference, AIC weights is the relative likelihood of a model, f = smooth terms. Age and length models were fit on different datasets as more length data are available.

Model	(e)df	Deviance explained	AIC	Δ_i	AIC weights
Age-based models					
†f(age) + f(lon, lat) + f(haul) + year	358.29	75%	6,543	0	100.0%
f(age) + f(haul) + year	435.17	75%	6,661	118	0.0%
f(age) + f(lon, lat) + year	48.95	69%	7,397	854	0.0%
*age year	58.00	62%	9,064	2,521	0.0%
f(age) + year	31.97	62%	9,079	2,537	0.0%
Length-based models					
†f(length) + f(lon, lat) + f(haul) + year	461.24	77%	11,997	0	100.0%
f(length) + f(haul) + year	539.32	77%	12,106	109	0.0%
f(length) + f(lon, lat) + year	49.75	71%	13,999	2,002	0.0%
*length year	58.00	67%	15,825	3,828	0.0%
f(length) + year	31.92	66%	16,403	4,406	0.0%

Strait (Fig. 2.4). To better model this pattern, the spatial coordinates were rotated 30 clockwise to correspond to axes that reflect the cross-strait and along-strait orientations, and the CART model was refit. This rotation reduced the number of breaks in the maturity data and thus the number of regions needed for estimating data weights (Fig. 2.5). This approach to minimize the number of regions reduces the number of instances in which regions contain no trawl samples in a given year.

Annual estimates of maturity from the spatial and weighted spatial models were averaged by age for comparison to the maturity schedule used in the current stock assessment (base model). Compared to both the spatial and weighted spatial models the stock assessment maturity schedule overestimates the proportion of young (<age-4) mature fish and underestimates the proportion of

Table 2.3. The most parsimonious age-based and length-based models (see Table 2.2) evaluated using an equivalent dataset to allow for model comparisons. Where *age* = the numeric fish age, *length* = individual fish length, *lon* = longitude in decimal degrees, *lat* = latitude in decimal degrees, *year* = the year sampling occurred as a factor, *haul* = individual hauls that samples originated from, incorporated as a random effect, *(e)df* = model estimated degrees of freedom, AIC = Akaike information criterion, Δ_i = AIC difference, AIC weights is the relative likelihood of a model, *f* = smooth terms. Age and length models were fit on different datasets as more length data are available.

Model	(e)df	Deviance explained	AIC	Δ_i	AIC weights
f(length) + f(lon, lat) + f(haul) + year	348.87	76%	6,386	0	100.0%
f(age) + f(lon, lat) + f(haul) + year	358.29	75%	6,543	157	0.0%

mature fish from age-4 to age-7 (Fig. 2.6). Differences between the unweighted and weighted spatial models were not statistically significant.

In most years A_{50} and L_{50} was significantly lower for the spatial and weighted spatial models compared to the base model (Fig. 2.7 and Fig. 2.8). There is a negative anomaly in all three estimates of A_{50} in 2004 (Fig. 2.7) that is even more visible in estimates of L_{50} (Fig. 2.8). The slope of the weighted spatial maturity at length (Fig. 2.9) model is steeper than for the spatial and base models. The weighted spatial model significantly differs from the base model for fork lengths between 40-52 cm with a greater proportion of the population mature at a smaller size for the spatially-weighted model.

Two sets of SSB estimates were used for evaluating the impacts of different models for estimating and incorporating maturity. The first is a comparison of SSB calculated from the mean maturity at age for all three models; this highlights differences between estimates using the methodology currently implemented in the stock assessment. The second is a comparison of SSB calculated from annually varying maturity estimates from all models. Estimates of SSB from the mean weighted and unweighted spatial models, based upon maturity in 2003-2013 though applied to all years (Fig. 2.10), were always greater than the base model estimates of SSB (Table 2.4). When SSB is estimated on annually varying estimates of maturity, the weighted and unweighted spatial models were again greater in all years during 2003-2013. However, only the unweighted spatial model can be evaluated for earlier years as it does not utilize spatial biomass weights. A retrospective examination shows some years when the base model produces larger estimates of SSB than the unweighted spatial model (Fig. 2.11).

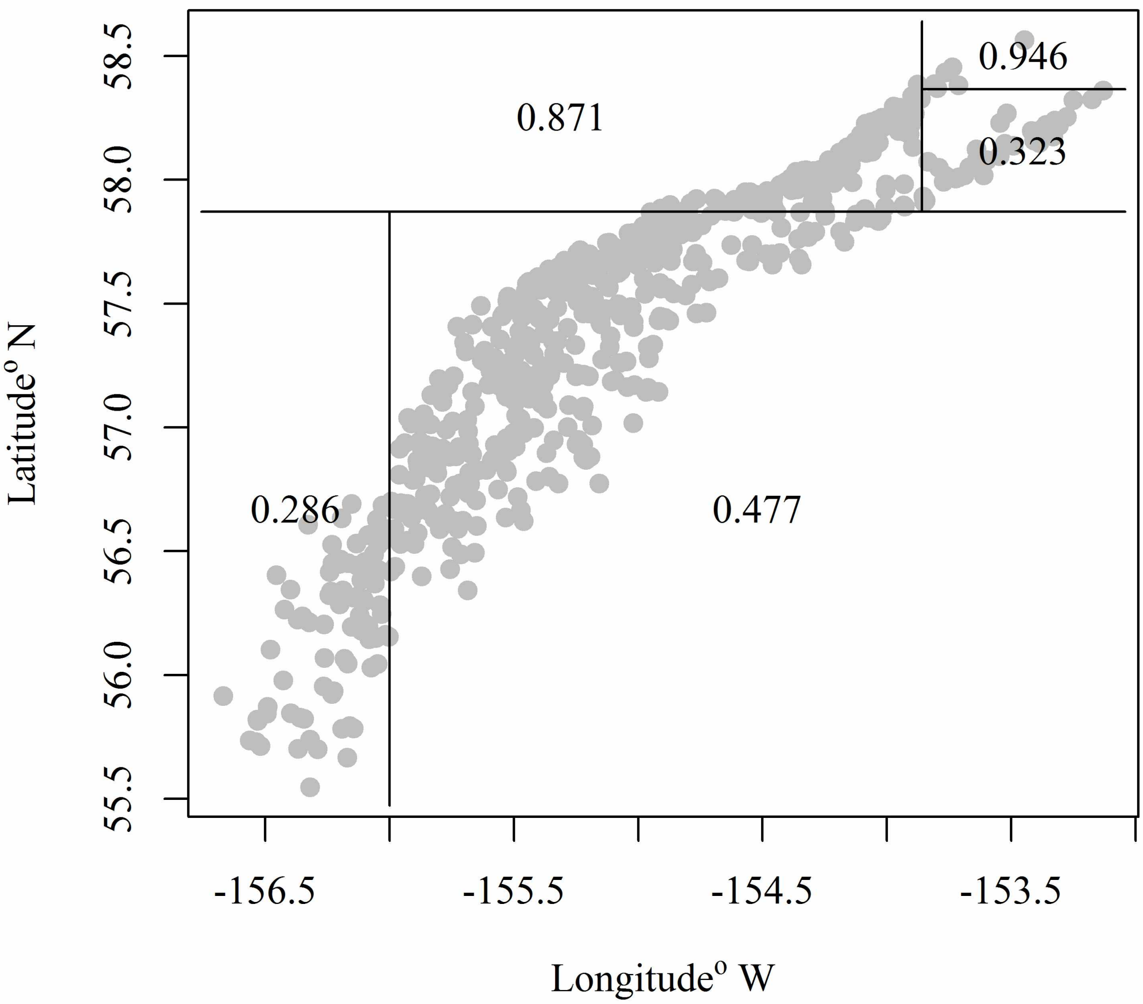

Figure 2.4. Proportion of female walleye pollock mature by area from a classification and regression tree model for the Gulf of Alaska. Numbers indicate the proportion mature in a given area.

Discussion

Our analysis highlights the importance of considering the sampling scheme for collecting biological data used to estimate population parameters. We discovered prominent temporal and spatial patterns in maturity of walleye pollock in Shelikof Strait that may impact both our understanding of the biology and management of the species. There have been only a few attempts to evaluate latitudinal gradients in maturity in gadids (Yoneda and Wright, 2004; Brander, 2005; Olsen et al.,

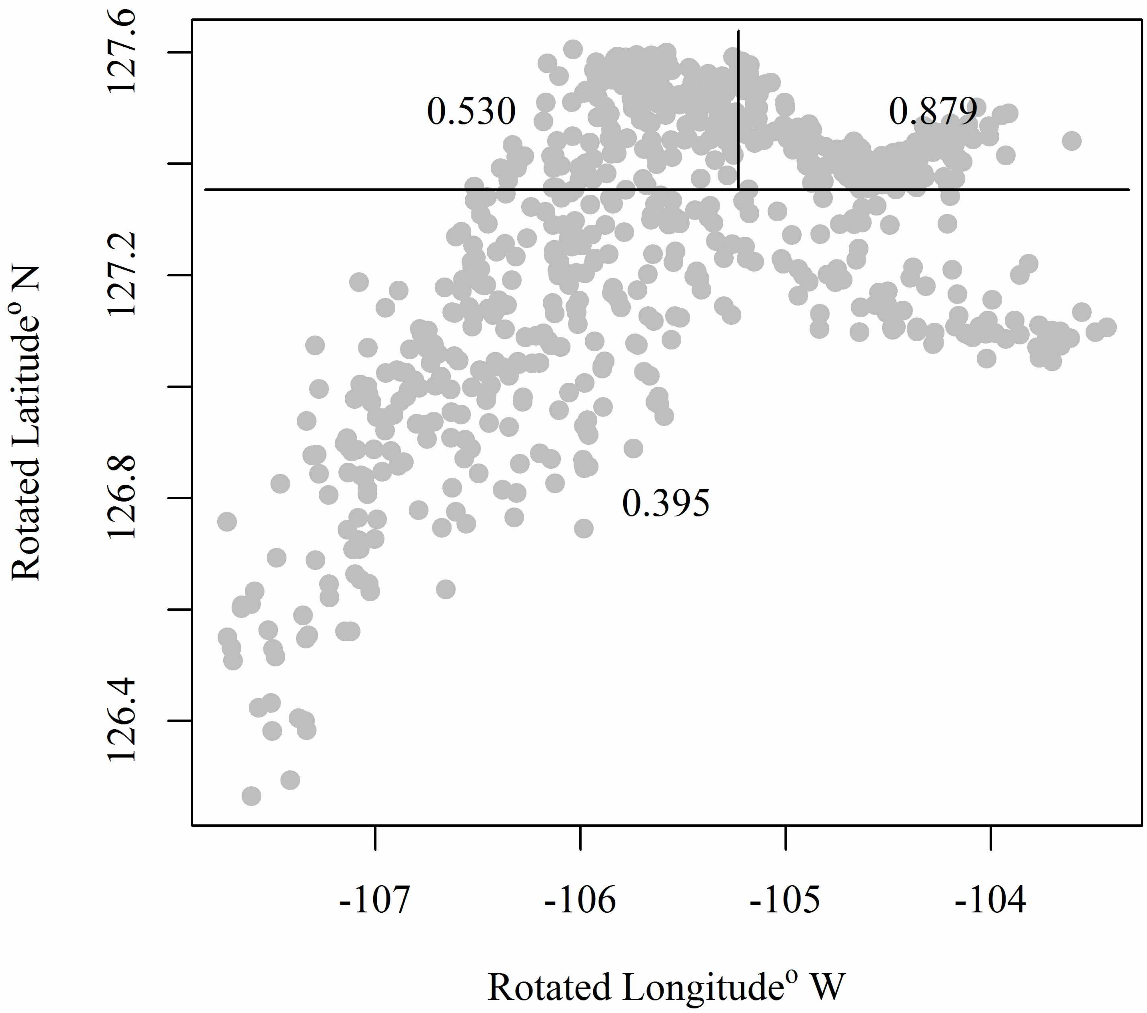

Figure 2.5. Classification and regression tree model results for the proportion of female walleye pollock that are mature by location in the Gulf of Alaska for data rotated 30°clockwise. Numbers indicate the proportion mature in a given area.

2002; Thorsen et al., 2010) or other species (Hay, 1985; Silva et al., 2006; Hay et al., 2008; Farley et al., 2014), examples of intra-stock spatial variability are rather limited (Stahl and Kruse, 2008b; Silva et al., 2006; Winton et al., 2014). For instance, both L_{50} and length at age of pollock tend to decrease with increasing latitude (Stahl and Kruse, 2008b), consistent with observations of higher growth rates in the southern Bering Sea (Lynde et al., 1986; Shuck, 2000). In addition, interannual variability in L_{50} was inversely related to annual estimates of biomass of age 1+ pollock in the

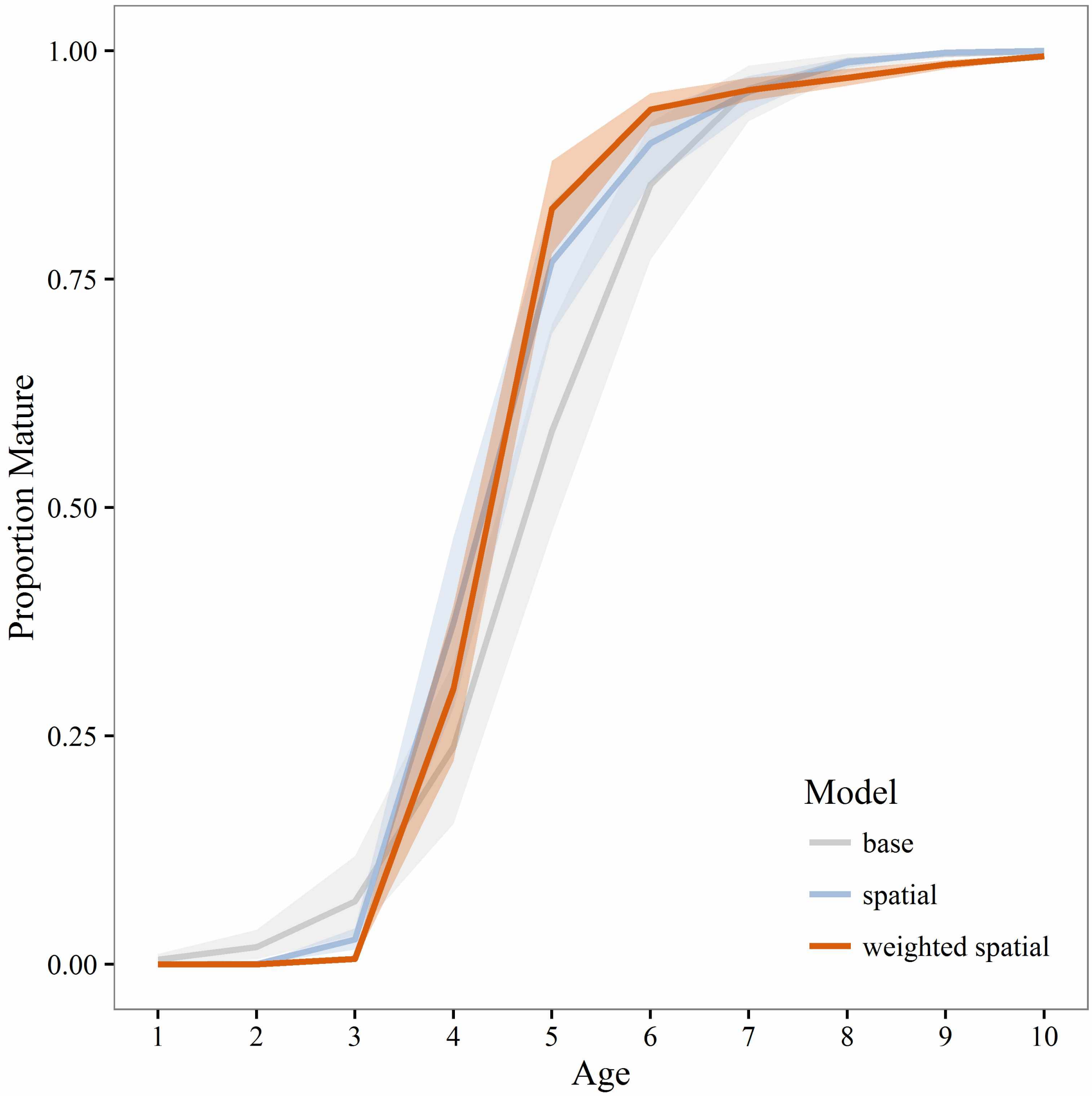

Figure 2.6. Mean proportion mature at age for walleye pollock in the Gulf of Alaska during 2003-2013. Estimates represent the base, unweighted and weighted spatial models. Shaded areas are 95% bootstrap confidence intervals.

eastern Bering Sea, providing evidence of density dependent growth (Stahl and Kruse, 2008b). One confounding factor for developing maturity estimates that incorporate spatial information is the need to link disparate maturity and spatial abundance data. The approach that we outlined provides a method for identifying and incorporating observed spatial variability in a manner that is easily implemented and adaptive to changes in spatial structure (i.e., does not assuming fixed boundaries) and can be utilized for other species.

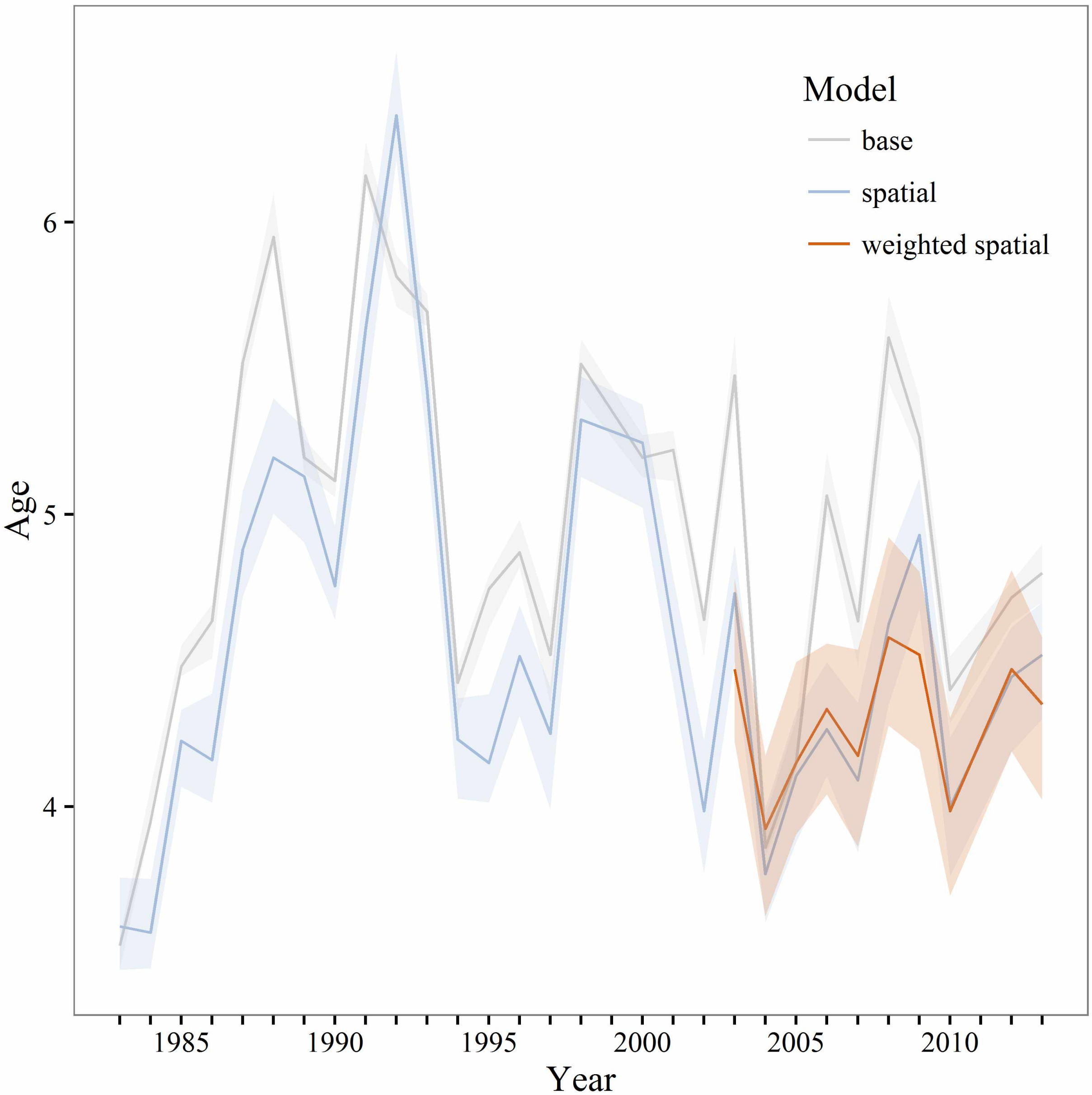

Figure 2.7. Estimates of 50% maturity at age (A_{50}) for the base, unweighted and weighted spatial models. The base and unweighted spatial models are estimated from 1983-2013, the weighted spatial model is estimated from 2003-2013. Shaded areas are 95% model estimated confidence intervals.

Potential reasons for spatial variability in maturity rates are wide ranging, and include temperature differences, changes in growth rates, population structure, migration or aggregation, and resource availability. Pollock in Shelikof Strait are considered a single genetic stock, inhabit a reasonably homogeneous environment (e.g., similar temperatures, salinities, and depths across the region), confounding our ability to uncover mechanisms responsible for the observed spatial

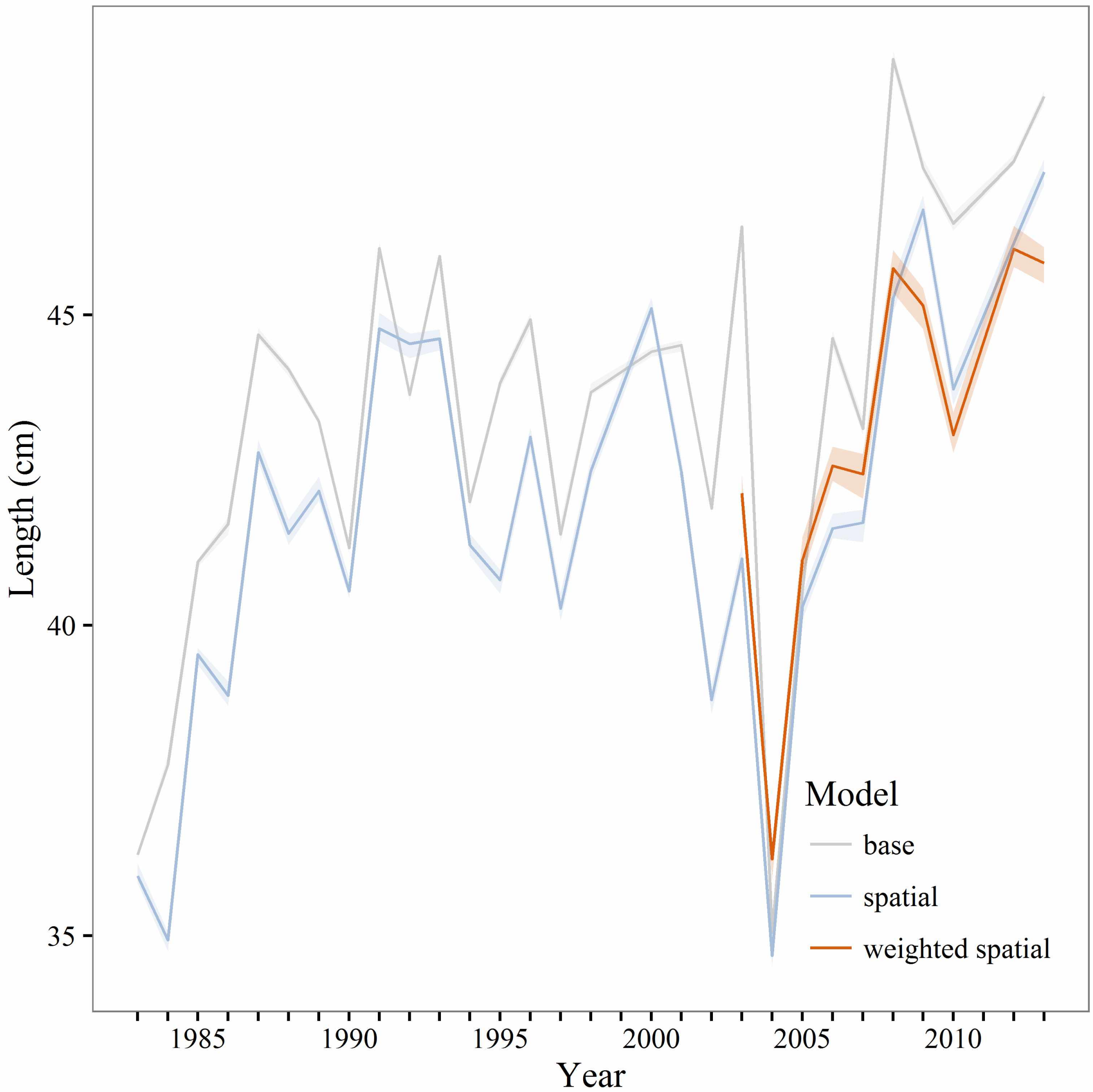

Figure 2.8. Estimates of 50% maturity at length (L_{50}) for the base, unweighted and weighted spatial models. The base and unweighted spatial models are estimated from 1983-2013, the weighted spatial model is estimated from 2003-2013. Shaded areas are 95% model estimated confidence intervals.

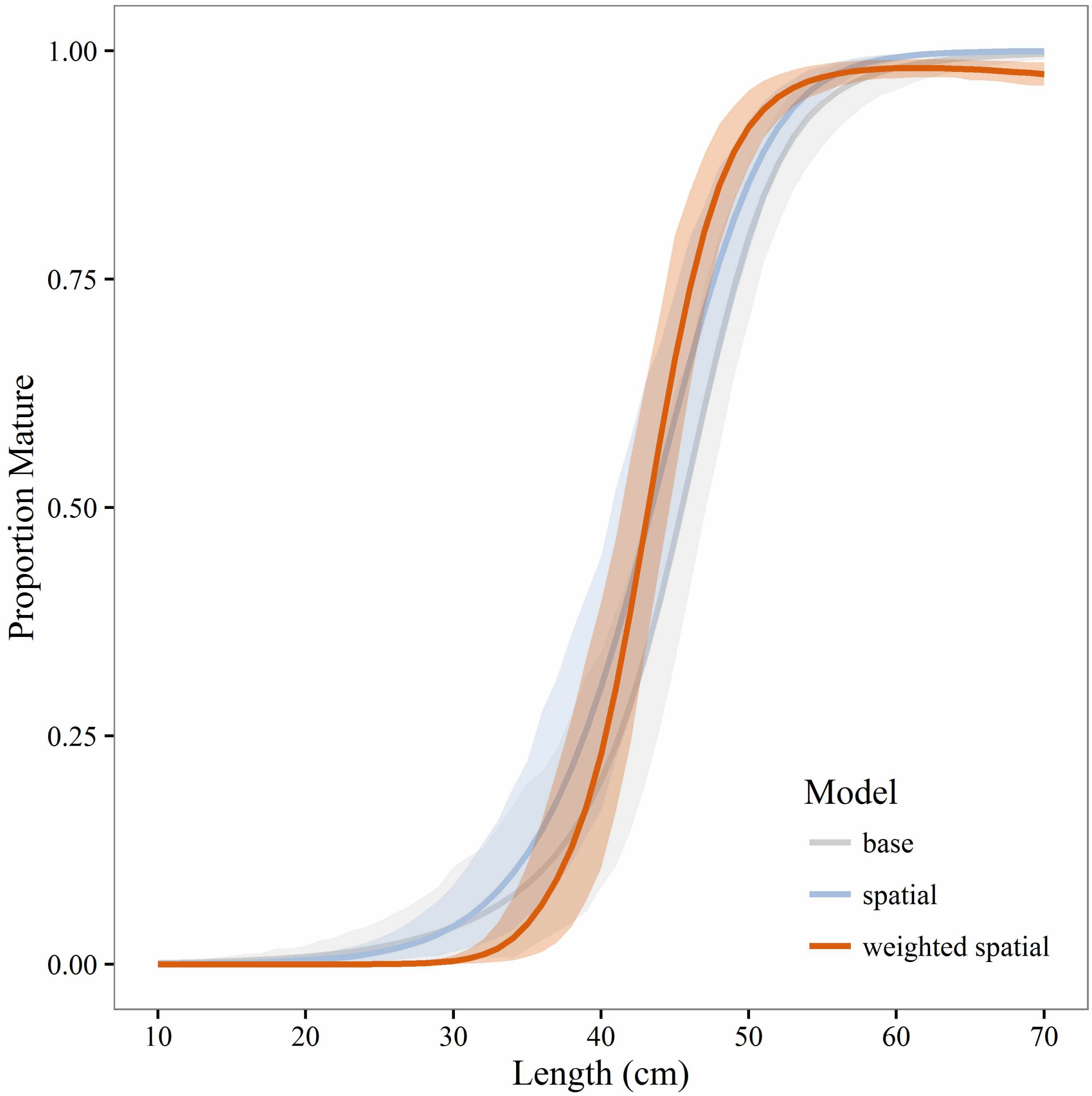

Figure 2.9. Mean proportion mature at length for walleye pollock in the Gulf of Alaska during 2003-2013. Estimates represent the base, unweighted and weighted spatial models. Shaded areas are 95% bootstrap confidence intervals.

trend in maturity. However, areas of pollock spawning locations were not found to be related to transport or temperature in Shelikof Strait (Bacheler et al., 2009). Likewise, in the eastern Bering Sea, temperature does not appear to drastically change the spatial pattern of pollock spawning although seasonal warming coincides with the progression of the spawning season (Bacheler et al., 2012).

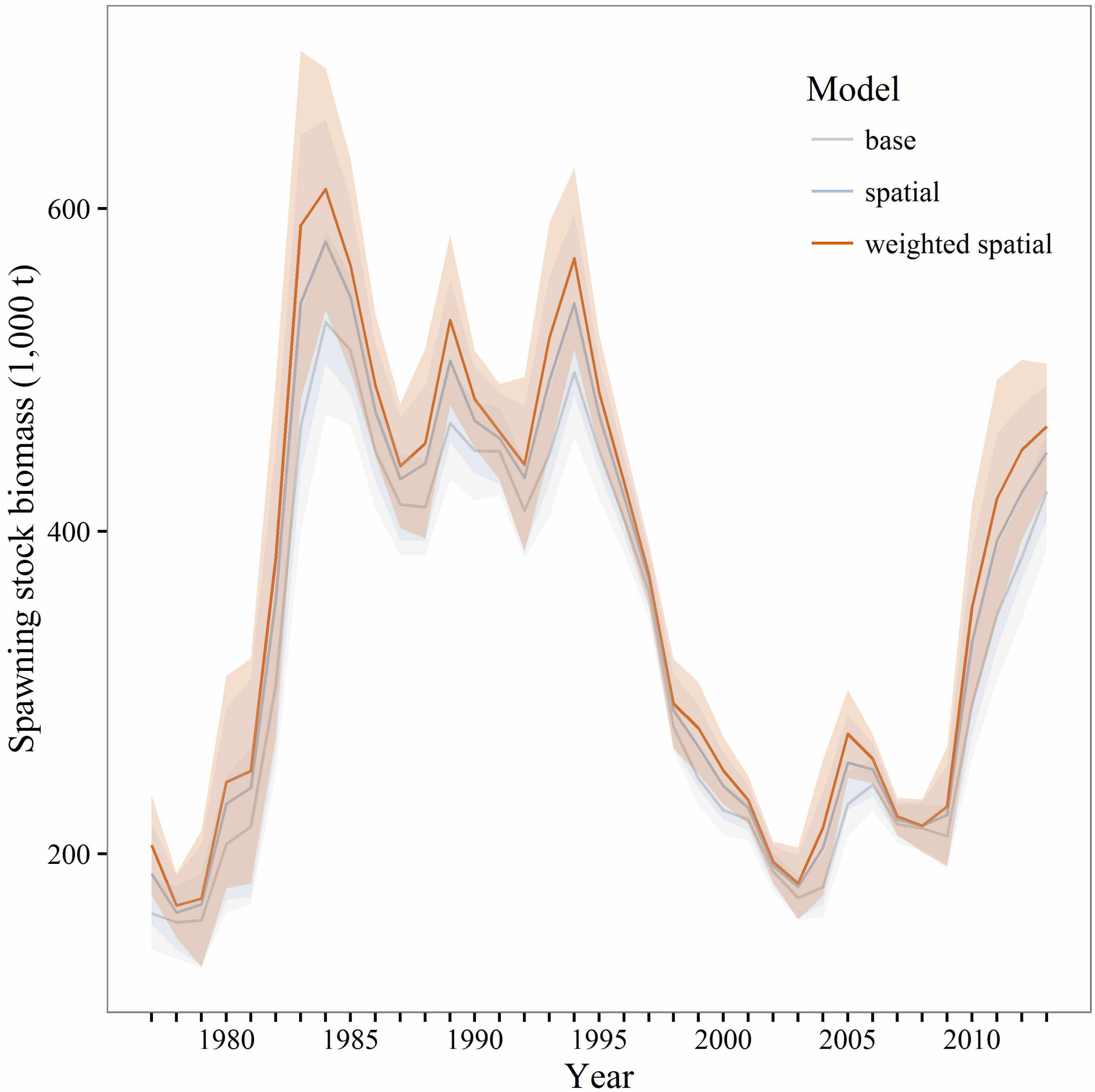

Figure 2.10. Estimates of walleye pollock spawning stock biomass (thousands of tons) for the Gulf of Alaska based upon age-averaged maturity estimates for 2003-2013.

The spatial and weighted spatial model estimates of maturity indicate that fewer fish younger than age-4 are mature and more fish older than age-4 are mature when compared to the current maturity ogive used in annual stock assessments. When the maturity estimates are incorporated into stock assessment estimates of abundance there is a 4.7 to 11.9% difference increase in average SSB, depending on the maturity estimate used from 2003-2013. Using any estimate, the current strategy appears to be conservative under recent conditions, leading to a consistent underestimate

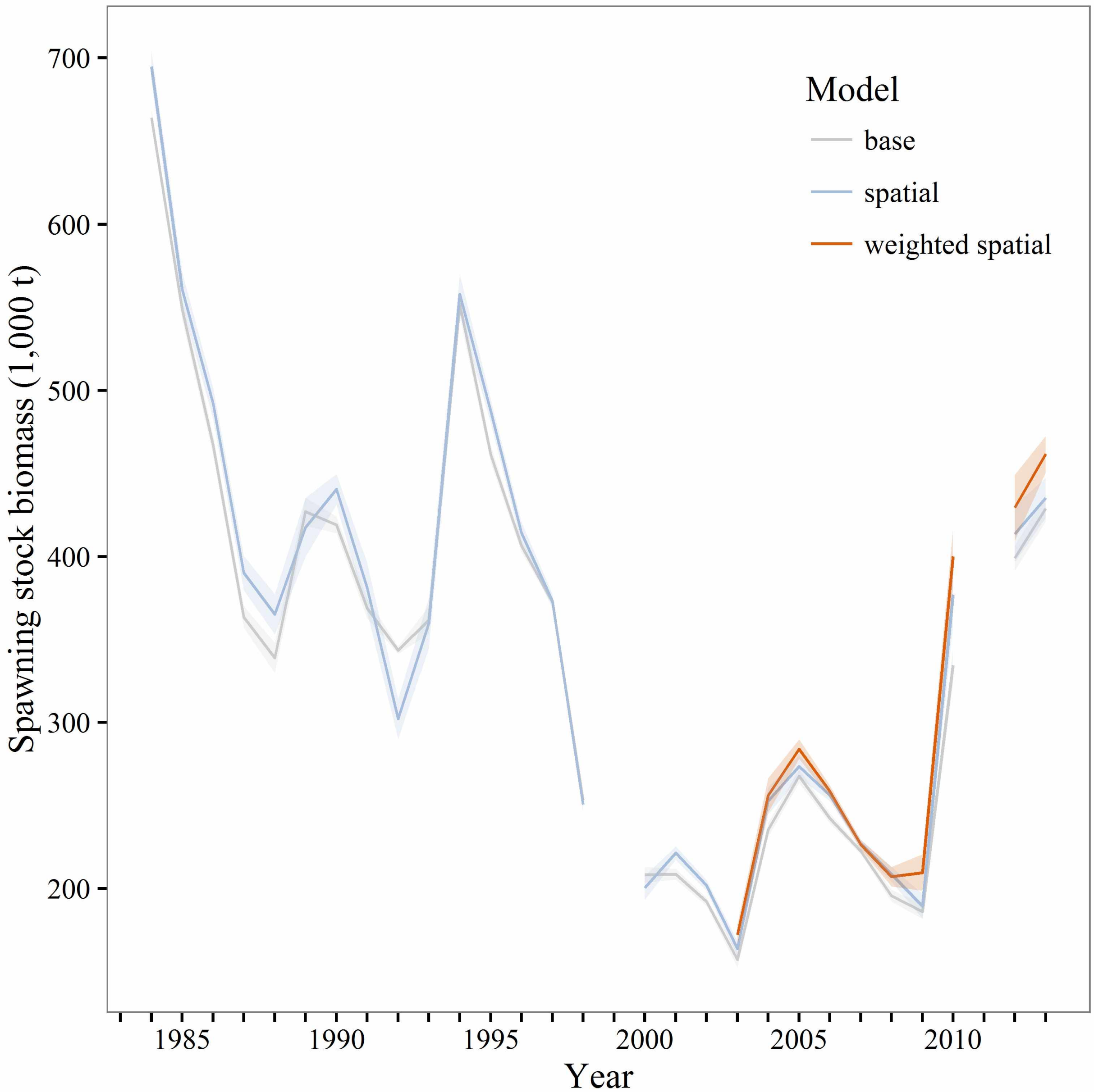

Figure 2.11. Estimates of walleye pollock spawning stock biomass (thousands of tons) for the Gulf of Alaska based upon annually varying maturity estimates. The base and unweighted spatial model are calculated for 1983-2013, the weighted spatial model is constrained by available abundance at location data and is calculated for 2003-2013.

Table 2.4. Differences between spatial or weighted spatial and base maturity model estimates of spawning stock biomass (1,000 t). Estimates of spawning stock biomass were estimated upon either mean or annually varying maturity estimates over 2003-2013.

	Mean maturity		Annual maturity	
SSB	Spatial	Weighted	Spatial	Weighted
mean	21.1	33.5	12.7	23.5
% diff	+7.6	+11.9	+4.7	+8.6
min	1.7	4.59	3.2	3.8
max	45.7	71.9	42.4	65.5
sd	15.6	25.3	11.5	17.1

of SSB for the time period evaluated. However, it is possible that this bias could be reversed in the future. Knowing that there is a spatial gradient in maturity a sampling design that works in conjunction with the "ground truth" hauls taken during hydroacoustic surveys may provide for more accurate estimates of maturity, or at least provide an indication of changing spatial biases. One such sampling design could be in the form of a limited number (6-8) of fixed trawl locations that are spatially separated and annually sampled in addition to the current sampling methodology.

As a caveat it should be noted that estimates of SSB in this study are based upon abundance for pollock in the whole of the GOA, not just Shelikof Strait. While the maturity estimates herein take into account spatial variability and relative abundance in Shelikof Strait, they do not account for possible spatial variability in the weight of pollock. This could be addressed by estimating SSB as the product of maturity at length and the spatial biomass at length, though this would not account for areas outside of Shelikof Strait. This method would, however, create a mismatch with a length-based estimate of maturity being incorporated into an age-structured stock assessment. This may well be a desirable objective particularly as length may be better associated with maturity as the process of maturation is likely to be driven by fish size as opposed to fish age, additionally length measurements are easier to obtain and are more precise than age estimates (Farley et al., 2014).

Another aspect that could influence the maturity estimates is the determination of female spatial abundance. This study assumes an even ratio of females to males, however trawl samples have been taken that are predominantly one sex. If sex ratios have strong spatial patterns the regional estimates of pollock maturity could be greatly influenced. Although lengths and ages are recorded by sex, methods have not yet been implemented for producing pollock biomass estimates by sex.

Our results are relevant to ecosystem-based fisheries management (EBFM), an approach that is broadly adopted by the North Pacific Fishery Management Council (NPFMC) for groundfish fishery management off Alaska (Witherell et al., 2000). For instance, pollock are important prey of Steller sea lions (*Eumetopias jubatus*), a large pinniped whose abundance west of Cape Suckling in the central Gulf of Alaska (144°W) declined severely in the 1970s to 1990s. Because of concerns that fishing on pre-spawning pollock could cause shifts in their spatial distribution and abundance that adversely affect sea lion foraging efficiency (Shuck, 2000), the NPFMC implemented several precautionary measures, including area closures near sea lion rookeries and haulouts, as well as spatial and temporal apportionment of total allowable catches (TACs) into smaller sub-TACs to prevent localized prey depletions (Witherell et al., 2000). Further, a better understanding of biotic and abiotic factors affecting spatial and temporal patterns in maturity is consistent with EBFM, an approach that strives to balance diverse societal objectives by taking account of knowledge and uncertainties in biotic, abiotic and human components of ecosystems and their interactions. As marine ecosystems can exhibit complex behaviors, it is crucial for fishery managers to maintain resistance and resilience of exploited populations (Bacheler et al., 2009). Thus, overfishing by highly size-selective fisheries are to be avoided, as such circumstances may lead to fishing-induced evolution of key biological traits, such as size of maturity; probabilistic maturation reaction norms may help detect such genetic effects (Lynde et al., 1986). However, the pollock fishery is managed with conservative harvest rates (Dorn et al., 2012, 2013) and interannual variability in A_{50} and L_{50} do not display directional trends that would be expected to arise from such genetic effects.

Although this study cannot address all of the components necessary for accurately determining maturity of GOA pollock, it clearly demonstrates that there is spatially explicit variability in maturity within Shelikof Strait. In this case, accounting for this variability increases the estimate of SSB. This has implications for estimates of stock productivity and therefore the harvest control rules used to manage this valuable fishery. Further it demonstrates a need for defined maturity sampling strategies that increase the ability to determine spatial and temporal trends in maturity and assure that catch specifications are determined upon the most accurate information possible, given the various constraints on resource assessment surveys. An important next step is to investigate ecological relationships between spatiotemporal variability in maturity and potential biotic and abiotic drivers. A better understanding of maturity trends and their relationships with ecological drivers could be incorporated into management strategy evaluations to evaluate management options for sustainable fisheries under climate change (Hollowed et al., 2009; Ianelli et al., 2011).

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Chapter 3

Temporal variation in the reproductive potential of walleye pollock *Gadus chalcogrammus* in the Gulf of Alaska[I]

3.1 Abstract

Relationships among body condition, population abundance, environmental variables, the probability of being mature, and relative fecundity were examined for female walleye pollock *Gadus chalcogrammus* in the Gulf of Alaska using generalized additive mixed effects models. Walleye pollock body condition is density-dependent, declining with cohort size. After accounting for the effects of length, age, location, year, and sample haul, condition has a positive effect on the probability of a fish being mature. Similarly, condition has a positive effect on relative fecundity, after accounting for length, age, egg diameter, and sample haul. A positive, but weaker, relationship is observed between depth-integrated summer ocean temperature and maturity and depth-integrated winter ocean temperature and fecundity. Chlorophyll-*a* concentration, as a measure of ocean productivity, has a dome shaped relationship with maturity, with the greatest proportion mature at a concentration of 2.3 mg/m^{-3}. As Chlorophyll-*a* concentration increases, the potential fecundity estimates by age decline. Variations in body condition, environmental variability, and population size have a direct influence on the estimated reproductive potential (RP) of the fish stock through both differences in the maturation schedule and total egg production. Over some periods our estimates of RP differ from estimates of female spawning stock biomass reported in the annual stock assessment, though the general trends are similar. The bulk of observed differences are due to underestimating the total egg production of age-4 and age-5 fish and overestimating the spawning stock biomass of age-10 fish. Alternative estimates of annual RP, particularly total egg production, may provide more accurate estimates of annual reproductive output than does spawning stock biomass. In addition, relationships to density-dependent and density-independent factors provide informative predictions that can be incorporated into stock assessment analyses.

3.2 Introduction

Sustainable fishery management necessitates maintaining fish stocks at levels that are resilient to exploitation. Information, such as stock biomass and structure, maturation rate, sex ratio, and fecundity, are sometimes available to inform managers about reproductive potential (RP) or total egg production (TEP), which can be used to determine stock resilience and capacity to re-

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build. However, in most cases, this biological information is not available and exploited marine fish stocks are managed instead by applying a harvest control rule to mature female biomass or spawning stock biomass (SSB) as estimated by an age-structured assessment model. In such cases, SSB is assumed to be a proxy for TEP with an assumed proportional relationship (Beverton and Holt, 1957).

Fish stocks often exhibit phenotypic plasticity in fecundity and maturity, which are often related to biological factors, such as stock density (Rijnsdorp et al., 1991; Marshall, 2009), fish size or age, and other indices of individual fish condition (Horwood et al., 1986; Rijnsdorp et al., 1991; Kjesbu et al., 1998; Blanchard et al., 2003; Murua et al., 2003) as well as environmental factors such as temperature and prey availability (Kjesbu et al., 1998). For these reasons, TEP is likely to be more dynamic than SSB (Marshall, 2016). Environmental conditions can influence fecundity and maturity through both direct and indirect effects reflected in growth and nutritional status (Lambert et al., 2003). For instance, temperature and ocean productivity (prey availability) regulate most physiological processes and govern the amount of energy available for somatic growth and gonadal development. Given that biotic and abiotic factors can lead to changes in TEP, it is important to examine reproductive parameters, such as fecundity and maturity, to ensure that estimates of SSB do not misspecify stock resilience.

The walleye pollock *Gadus chalcogrammus* (hereafter pollock) fishery in the Gulf of Alaska (GOA) is managed by applying a harvest control rule to estimates of SSB from an age-structured assessment model. The SSB is based in part upon a maturation schedule, the proportion of female fish that are mature at a given age. In the annual stock assessment, maturity estimates for the GOA are currently specified as the average maturity-at-age from 1983 through the most recent winter assessment (Dorn et al., 2016). Estimates of fecundity, the number of eggs that an average female pollock releases during a year, are not currently incorporated directly into the stock assessment. The SSB is used as a surrogate for fecundity at age to calculate mean generation time for the GOA pollock stock (Dorn et al., 2016).

The pollock stock assessment using SSB might be improved by using estimates of egg production obtained from contemporary fecundity and maturity estimates under current stock levels and climate regimes. Interannual variability of pollock maturity has been observed in the eastern Bering Sea (Stahl and Kruse, 2008b) that may lead to a greater contribution toward SSB by younger fish than is currently modeled (Ianelli et al., 2010). A recent examination of spatial and temporal variability in pollock maturity in the GOA (Williams et al., 2016) revealed an underestimation of SSB when this variability is ignored. No recent examinations in GOA pollock fecundity have been undertaken, although population demographics have changed substantially in the past 30 years. Variations in the relationships of fecundity, in lieu of SSB, and stock size differ for some gadoids, such as Atlantic cod *Gadus morhua*, because fecundity per unit of biomass can vary with time (Marshall et al., 2006). This finding can affect biological reference points used to manage fisheries. For instance, Spencer and Dorn (2013) used simulation modeling of the GOA pollock stock assessment to show how reproductive dynamics affect stock productivity. They found that application of weight-specific relative fecundity (i.e., increasing fecundity per unit mass with increasing body weight) increased estimates of F_{MSY} (fishing mortality rate at maximum sustainable yield) relative to an estimate using SSB as reproductive potential. This is a consequence of higher stock productivity associated with greater reproductive output (relative to an unfished stock) with increasing weight-specific fecundity. Estimation of functional relationships between temporal and spatial variability in fecundity and maturity under different stock biomasses and environmental conditions may lead to improvements in the pollock stock assessment.

The National Marine Fisheries Service (NMFS) has monitored pollock biomass and reproductive stages in the GOA for almost three decades. Using these samples, we examined how pollock fecundity and maturity relate to stock and environmental variability. We considered the following hypotheses: (1) pollock abundance does not compromise body condition, fecundity, or maturity (no density-dependence); (2) temperature directly influences the metabolic rate of pollock such that colder years lead to reduced fecundity (Pörtner et al., 2001) and reduced numbers of mature females during either the growing season (April to October) or during the final stages of maturation (November to March); and, (3) increased ocean productivity during spring and summer translates into increased consumption of prey by pollock and accumulation of energy reserves for reproduction (Kjesbu *et al.* 1998). That is, the proportion of mature pollock at age or length, as well as their fecundity, increases with increased ocean productivity.

To test these hypotheses, a suite of models incorporating biological and environmental variables were examined. Biological variables used to test hypothesis 1 include stock biomass (density), abundance-at-age (Dorn *et al.* 2016), and a condition index based on a predicted weight (Blanchard *et al.* 2003). Primary oceanographic variables include temperature and an ocean productivity index. To test hypothesis 2, we used depth-integrated temperature anomalies available from a Regional Ocean Modeling System (ROMS). To test hypothesis 3, we considered two indices of productivity, including a measure of the length of the growing season (duration between spring and fall transitions from modeled data) and a satellite-derived measure of phytoplankton standing stock based on ocean color for time periods when it is available (extensive cloud cover in the region limits data availability).

3.3 Materials and Methods

3.3.1 Biological data

Pollock have been sampled in the western Gulf of Alaska (Figure 3.1; Table 3.1) during spring acoustic surveys since 1983 (NMFS 2013). Macroscopic estimates of female maturity have been determined using a 5-stage (Stahl and Kruse, 2008a) or 8-stage key (Williams, 2007), which were condensed to immature/mature with pre-spawning and later stages considered mature. Fish were measured for fork length to the nearest cm and weighed in grams; ages were determined by the AFSC Age and Growth Program (Matta and Kimura, 2012). Ovary samples of mature pollock were collected opportunistically from random AFSC trawl surveys and stored in 10% buffered formalin solution. Each sample has associated location and date of capture information as well as individual weight (g), fork length (cm) and age information. The spatial extent of these data is dependent upon the sampling location of the NMFS survey trawls and incorporates regional variability. Samples were typically collected from winter pre-spawning cruises, allowing us to examine annual variability.

Population abundance

Four measures of population size in numbers and weight were calculated from Dorn et al. (2016). Total abundance was the annual sum of the assessment estimated number of pollock over ages 1-10 within a year. Cohort abundance was the assessment estimated number in a single pollock age cohort, by year. Biomass was calculated as the product of the number of fish at age and their weight at age. These abundance indices were also lagged for examination of the previous year's abundance or biomass effects.

Fecundity estimation

Viable archived pre-spawning ovary samples were analyzed by the AFSC to provide estimates of fecundity using the gravimetric method (Cooper et al., 2005). The gravimetric method involves weighing preserved ovaries, excising small cross-sections from the ovaries, weighing the samples to the nearest 0.001 g, and counting the number of eggs in the sample, with a target sample size of 1,000 eggs:

$$F_i = \frac{O}{w * n}, \tag{3.1}$$

where F_i is estimated individual potential fecundity, O is total ovary weight, w is subsample weight, and n is the number of oocytes in the subsample. The number of eggs in a subsample and the average oocyte diameter were calculated using a stereological method (Emerson *et al.* 1990). A more complete description of fecundity estimation is available in Appendix A.

3.3.2 Environmental Data

Stratification Index and Ocean Temperature

Temperature, salinity, and current velocity from the surface to 300 m depth, and sea surface height were estimated by an ocean circulation model based on the Regional Ocean Modeling System (ROMS) version 3.0. ROMS is a hydrostatic, primitive equation, generalized sigma-coordinate model. A full description of ROMS can be found in (Haidvogel et al., 2000, 2008; Shchepetkin and McWilliams, 1998, 2005; Shchepetkin, 2003), and references therein. The ROMS physical model is coupled to a lower trophic level nutrient-phytoplankton-zooplankton-detritus (NPZD) model with 11 compartments (Hinckley et al., 2009). Detailed descriptions of the coupled model, its parameter values, and its calibration using northern GOA Seward line observations are provided in Coyle et al. (2012). The ROMS model was initialized on January 1, 1997 and run continuously to December 31, 2012. Daily, tidally filtered averages of ocean variables were saved during the integration. We then used averages of weekly outputs for subsequent analyses.

A stratification index (STI) based upon point-wise weekly temperature and salinity profiles was created using the methods of Ladd and Stabeno (2012). The STI was based upon the profiles from the surface to 75 m depth. The stratification "on" date was defined as the first time in spring (March-June) (Table 3.2) when the STI goes above a threshold indicating that the GOA was stratified; the "off" date was the first time in the fall (September-November) when the STI drops below a threshold indicating that the GOA summer stratification had broken down. The stratification calculation deviated from Ladd and Stabeno (2012) in that December-January-February mean STI was removed from the directly calculated 75-meter STI before applying the threshold criteria. The reason for this is that the STI is not completely zero even in the winter months when the GOA remains slightly stratified due to a halocline.

Annual summer temperature was calculated as the depth-integrated (0-300 m) average temperature during dates when the STI was above threshold (stratified). This time series was adjusted to reflect the summer temperature in the previous year, because maturity and fecundity samples were collected in the spring and it was assumed that conditions during the previous growing season were most relevant to oogenesis. Annual winter temperature was calculated as the depth-integrated (0-300 m) average temperature during dates when the STI was below threshold (e.g., Julian day 280 in 1997 to Julian day 93 in 1998; Table 3.2).

Chlorophyll-*a*

Seasonal and interannual variability in chlorophyll-*a* (chl-*a*) concentrations during periods when the GOA was stratified were explored using MODIS-Aqua and SeaWiFS data from the Goddard Space Flight Center Ocean Color web site (https://oceancolor.gsfc.nasa.gov/). These data were combined to form a single time series (Zhang et al., 2006; Waite and Mueter, 2013), the spatial extent of the data was trimmed to reflect data for Shelikof Strait and weekly chl-*a* values were used for subsequent analyses.

3.3.3 Statistical analyses

An evaluation of whether abundance influences fecundity or maturity necessitates a definition of an index of body condition, determination of a relationship between body condition and biomass or abundance, as well as relationships between body condition and maturity or fecundity. The reason for these separate approaches is that there is no functional linkage between greater fecundity or increased probability of being mature in relation to abundance or biomass. However, there is evidence that fish body condition affects maturity and fecundity for many species (Morgan, 2004; Mion et al., 2018), and that density-dependent effects may influence body condition (Trippel1999). However, the incorporation of relative body condition (K_r) typically increases model performance although often at a non-significant level (Morgan, 2004; Uusi-Heikkilä et al., 2010).

The K_r for female pollock was calculated as:

$$K_r = W/\hat{W}, \tag{3.2}$$

where W is observed round weight and $\hat{W}$ is the predicted body weight (Morgan 2004) estimated using linear regression with log-transformed data to determine the allometric relationship:

$$\hat{W} = aL^b. \tag{3.3}$$

Estimates were corrected for bias per (Hayes et al., 1995). Body condition was estimated for all mature and immature individuals for incorporation in maturity estimation models and for mature, pre-spawning females for incorporation in fecundity models. Relationships between K_r and total population abundance, cohort abundance or biomass were modeled using generalized additive mixed-effects models (GAMMs) of the form:

$$\hat{K}_r = f_1(Length) \cdot Age + f_2(Abundance) + f_3(Haul) + Year + Mature + \varepsilon. \tag{3.4}$$

These GAMMs included length and abundance or biomass as a continuous variable. The haul that a sample originated from was included as a random effect, and year, age, and maturity status (immature/mature) were included as categorical variables. $\hat{K}_r$ was estimated using smooth functions (f_i) using maximum likelihood, where the maximum number of knots was set at 4 for explanatory variables (Wood, 2011). This model is set up so that length is smoothed seperated for each level of the age factor, as not all lengths are present at all ages. Multiple indices of population size from (Dorn et al., 2016) were examined; total annual abundance, annual cohort abundance, and total annual biomass, and lags of these measures.

GAMMs were also used for examining relationships between maturity or fecundity, population size and environmental covariates. A logistic GAMM that accounts for spatial and temporal variability was used to estimate maturity ($\hat{M}$, see Chapter 2 for a complete description of the model):

$$\hat{M} = f_1(Length) \cdot Age + f_2(Location) + f_3(Haul) + Year + \varepsilon. \tag{3.5}$$

A similar GAMM was examined for estimating potential fecundity F_p as a function of fork length, haul (as a random effect), mean egg diameter (continuous variable), and age as a factor. Egg diameter was included to account for different sized eggs of pre-spawning female pollock. Because maturity stage was determined macroscopically, egg diameter was included to account for different stages of prespawning fish. The base model was:

$$\hat{F}_p = f_1(Length) \cdot Age + f_2(Diameter) + f_3(Haul) + \varepsilon. \tag{3.6}$$

No relationship was observed between length and K_r; therefore both variables were included in the model. The fecundity model was fit using the gamma family distribution to account for increasing residual variance with a log link (Wood, 2011; R Core Team, 2017); the number of knots was restricted to a maximum of four.

Whether there are relationships between K_r, pollock abundance or biomass, temperature, or ocean productivity and the probability of being mature or fecundity was examined by updating the GAMMs to include the descriptor variables. The year explanatory variable was excluded from any models with variables on an annual time step (e.g., temperature). The relative explanatory power of models with and without K_r and environmental covariates, and the most parsimonious reduced models, were evaluated using the Akaike Information Criterion (Akaike, 1973; Burnham and Anderson, 2002, AIC) and comparisons of deviance explained. Ocean temperature and productivity were incorporated as covariates into the most parsimonious fecundity and maturity models using the same methods as described for the incorporation of K_r.

Reproductive potential

Three estimates of annual RP were calculated for comparison. The first estimate is the stock assessment estimate of SSB that incorporates mean maturity-at-age from 1983 through the most recent winter assessment (M_a):

$$SSB_y = \sum_{a=1}^{j} N_{ay} M_a W_{ay}, \tag{3.7}$$

where N_{ay} is the population number at age a in year y, and W_{ay} is the weight at age a in year y. The second estimate of RP is an estimate of SSB that incorporates time-varying maturity from Equation 5:

$$SSB_y = \sum_{a=1}^{j} N_{ay} M_{ay} W_{ay}. \tag{3.8}$$

A third estimate of RP is an estimate of TEP:

$$TEP = \sum_{a=1}^{j} N_{ay} M_{ay} (\hat{F}_p). \tag{3.9}$$

These indices were standardized to their means and variances for graphical comparison.

3.4 Results

The length-weight relationship of $\hat{W} = 0.0029\ L^{3.256}$ for all female pollock was statistically significant ($P < 0.0001$). The relationship for mature pre-spawning female pollock was $\hat{W} = 0.0038\ L^{3.196}$, which was also highly significant ($P < 0.0001$). A substantial amount of temporal variability in body condition by age was observed (Figure 3.2), along with a trend of declining K_r by age over all years. Pollock K_r exhibits a density-dependent relationship with annual cohort abundance by age (Figure 3.3). This relationship is statistically significant regardless of whether fish were mature or immature. The percent deviance explained by the model including cohort abundance is increased by 0.1% from a base model that excludes abundance (Table 3.3), likely due to allocating variance from the random effect to the population abundance covariate.

A suite of models were examined for both maturity and fecundity with an observed effect of K_r, winter temperature (fecundity), summer temperature (maturity), and chlorophyll-a. The maturity model with the second lowest AIC score (base model + K_r + summer ocean temperature + chl-a; Table 3.5) was selected as the top model. This model has greater parsimony than the AIC top scored model, as it has fewer model estimated degrees of freedom.

A positive relationship was observed between K_r and both the probability of a fish being mature and estimated fecundity by age. These relationships are significant and increase the deviance explained by 2.3% and 4.8% from the base maturity and fecundity models, respectively (Tables 3.4 and 3.5). Increases in K_r have the greatest effect on maturity of age-4, age-5, and age-6 fish (Figure 3.4), while the effects of K_r on fecundity are largest for older pollock, as indicated by steeper response slopes (Figure 3.5). The addition of depth-integrated summer ocean temperature incrementally increases the AIC model fits for maturity (Table 3.5), while winter ocean temperature is included in the top fecundity model (Table 3.4). There is a strong increase in the probability of being mature for ages greater than three if summer ocean temperature is greater than about 7.9°C (Figure 3.6).

The fecundity model indicated an increase in deviance explained with the inclusion of winter ocean temperature (Table 3.4). There is a general increase in fecundity associated with winter temperatures, with the effect increasing for older ages (Figure 3.7).

Chlorophyll-*a* concentrations, as a measure of ocean productivity, averaged over the STI "on" time period show different trends for maturity and fecundity (Figures 3.8 and 3.9). Maturity has a dome shaped response to chlorophyll-*a* with a peak at 2.3 mg/m^{-3}. Fecundity has a strong negative response to increased chlorophyll-*a* concentrations, with the largest effects observed at older ages. Both the fecundity and maturity models are highly descriptive in that they each explain over 80% of the variability observed in the dependent variable.

Trends in the three estimates of reproductive potential show periods of synchrony and asynchrony through time (Figure 3.10). Overall, trends are similar, however there are times such as in the mid-1990s when the stock assessment estimate of SSB is greater than the estimates of TEP and SSB based upon time-varying maturity. This relationship flips during 2010-2013, when TEP and SSB based upon time-varying maturity are greater than the estimate of SSB. The time varying estimate of pollock SSB is more similar to TEP. An examination of residuals by age and year show an age effect (Figure 3.11) whereby age-4 and to a lesser degree age-5 pollock TEP is being under-represented by the stock assessment estimate of SSB and older (e.g., age-10) pollock are being over-represented.

3.5 Discussion and Conclusions

Female pollock have a greater probability of being mature with greater fecundity if they are in better body condition. Increasing age-cohort abundance has a negative effect on body condition. This suggests that there is a negative density-dependent relationship between pollock cohort abundance and both maturity and fecundity. The strength of the relationships between body condition and both maturity and fecundity diminish the ability to recognize a signal from environmental and population size covariates. However, there are significant relationships observed for both maturity and fecundity with both ocean temperature and chlorophyll-*a* concentrations. When condition, ocean temperature, and chlorophyll-*a* effects are incorporated into estimates of RP for the GOA stock, there are divergent trends during some periods relative to the current assessment estimate of SSB.

Many species exhibit a positive relationship between maturity or fecundity and condition (Morgan, 2004). However, the scope of this relationship has not previously been examined for pollock in the GOA, though similar responses have been observed elsewhere (Hamatsu and Yabuki, 2007; Kooka, 2012). The influence of body condition on maturity and fecundity leads to periods when there is a sustained under- or over-representation of TEP relative to SSB. Theoretically, TEP is a better representation of the RP of a stock than SSB (Pérez-Rodríguez et al., 2011). If we accept this assumption then the RP was often overestimated in the 1980-1990s and underestimated in the late-2000s. If these periods continue for a number of consecutive years they will lead to biased estimates of the overfishing level (OFL) and acceptable biological catch (ABC) from which total allowable catches are set. It needs to be noted though that accurate estimates of RP can be difficult to obtain and may not necessarily improve upon estimates of spawner-recruit relationships (Morgan and Brattey, 2005; Kell et al., 2015). However, TEP may provide a better understanding of the underlying dynamics influencing a population than SSB (Kell et al., 2015). Therefore, our work highlights the need to examine multiple estimates of RP.

While significant environmental environmental and population size covariates are observed in this study, their ability to explain variability in pollock maturity or fecundity is low. This does not mean that these variables have limited or no influence. Theoretically, ocean temperature, population size, and ocean productivity influence the energy allocation of a fish to their gonadic and somatic growth. However, these effects may be indirectly incorporated through the observed effects of body condition. In addition, lack of a stronger environmental relationships may indicate that the spatio-temporal resolution of the data may be insufficient for fully addressing these questions, or that the effects are indirect (such as through effects on K_r). Alternatively, the relatively weak environmental signals may indicate that processes inherent to reproductive potential (e.g., fecundity at age) are strong and pollock may exhibit less phenotypic plasticity than originally anticipated.

Incorporating estimates of body condition into stock assessments may provide more accurate estimates of RP and assist in maintaining stocks at sustainable levels (Morgan and Brattey, 2005). Because the differences in SSB and TEP that we observed are consistent (e.g., biased against age-4 and age-5 fish), additional research is needed to explore under which conditions the age/length composition exerts the greatest influence on RP. A management strategy evaluation (MSE) exploring how TEP performs relative to the current harvest control rule based upon estimates of SSB may provide insight into such conditions (Kell et al., 2015). A MSE of this nature could be used to examine whether the current or alternative management strategies are robust to variability and uncertainty in the the reproductive biology of the walleye pollock stock. Further, continued collection of ovary samples is necessary to maintain contemporary estimates of fecundity and total egg production and will provide stock assessment authors with the data necessary for exploring the interactions between stock structure and management policies. Including reproductive biology (growth, fecundity, maturity) and observed relationships with environmental variability and population size within a MSE will allow for an estimation of the consequences of these variables on harvest strategies.

Some of the results presented in this paper may be incorporated into the stock assessment immediately. A maturity estimate that accounts for spatial and temporal variability is likely to be less biased than an the average maturity at age that is currently utilized. Additionally, fecundity estimates can be incorporated for estimating mean generation time for the GOA stock. Further examination of pollock body condition shows great potential for being able to link environmental and population abundance covariates to RP. These examinations may inform managers and policy makers of anticipated population changes coupled with climatic change.

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Table 3.1. Number of length and weight samples available for female pollock from annual surveys in Shelikof Strait, with the associated number of the samples that were mature and the number of individuals that were aged during 1983-2013.

Year	Samples	Mature	Aged	Year	Samples	Mature	Aged
1983	688	388	0	2000	1294	510	363
1984	937	755	0	2001	1399	357	378
1985	1252	763	345	2002	667	301	326
1986	817	292	271	2003	752	131	309
1987	670	322	580	2004	712	399	440
1988	640	111	339	2005	482	264	335
1989	546	229	442	2006	691	459	487
1990	1740	1052	1117	2007	453	238	320
1991	675	273	567	2008	426	100	248
1992	643	182	642	2009	430	111	301
1993	1315	620	624	2010	462	146	244
1994	2782	2295	632	2012	523	191	372
1995	1243	723	575	2013	514	266	386
1996	2198	1349	775				
1997	1547	893	853				
1998	1282	478	784				

Table 3.2. Annual stratification start and end days, chlorophyll-*a* concentrations and depth-averaged ocean temperatures. The duration is the number of days that the stratification index was "on" during the summer.

	Julian day			Chl-*a*	Ocean Temp °C	
Year	Start	End	Duration	mg/m^{-3}	Summer	Winter
1998	119	279	161	1.61	8.45	6.15
1999	94	265	172	1.88	7.78	6.00
2000	124	273	150	2.19	7.42	5.58
2001	95	273	179	2.43	7.57	6.71
2002	79	270	192	2.17	7.87	6.30
2003	113	288	176	2.28	7.92	6.90
2004	85	270	186	2.10	8.26	6.73
2005	99	288	189	1.75	8.06	6.22
2006	115	284	170	2.15	8.98	6.23
2007	131	284	154	2.35	8.67	5.43
2008	139	279	141	2.12	8.14	5.94
2009	128	272	145	1.80	8.26	5.94
2010	119	278	160	2.14	7.95	6.73
2011	138	271	135	2.19	9.19	6.64
2012	138	259	122	3.02	8.35	8.27

Table 3.3. Model ranking for determining relationships between body condition (K_r) and abundance. Four measures of population abundance from Dorn et al. (2016) were examined: total abundance (numbers), total biomass (weight), age cohort abundance, and age cohort biomass. These measures were also examined with a one year lag. The base model is represented in eq. (4) in the text. The edf = model estimated degrees of freedom, AIC = Akaike information criterion, ΔAIC = AIC difference, the deviance explained is a pseudo R^2 statistic.

Model	edf	AIC	ΔAIC	Deviance explained
base + cohort abundance	395.1	-23,008.36	0.00	25.9
base	395.3	-22,984.01	24.4	25.8
base + cohort biomass	397.5	-22,925.18	83.2	26.6
base + lagged cohort abundance	401.1	-22,919.55	88.8	26.6
base + lagged cohort biomass	400.7	-22,914.28	94.1	26.6
base + lagged total abundance	397.6	-22,891.09	117.3	26.4
base + total abundance	397.6	-22,891.09	117.3	26.4
base + total biomass	397.6	-22,891.09	117.3	26.4
base + lagged total biomass	397.6	-22891.09	117.3	26.4

Table 3.4. Model ranking for determining relationships between fecundity and body condition (K_r) ocean temperature, and ocean productivity. The edf = model estimated degrees of freedom, AIC = Akaike information criterion, ΔAIC = AIC difference, the deviance explained is a pseudo R^2 statistic.

Model	edf	AIC	ΔAIC	Deviance explained
base + K_r + winter temp + chl-*a*	19.9	9,844	0.0	86.3
base + K_r + STI duration	20.3	9,846	1.8	86.3
base + K_r + summer temp + STI duration	19.5	9,864	20.2	85.5
base + K_r + summer temp	18.2	9,867	22.9	85.3
base + K_r + summer temp + chl-*a*	19.0	9,868	24.3	85.4
base + K_r + winter temp	17.0	9,868	24.3	85.2
base + K_r	18.8	9,881	36.5	84.9
base + summer temp	14.0	9,961	117.0	80.8
base + winter temp	19.7	9,984	140.0	80.2
base	19.6	9,986	142.0	80.1
base + chl-*a*	20.6	9,986	142.0	80.2
base + STI duration	20.6	9,987	143.0	80.2

Table 3.5. Model rankings for determining relationships between maturity and body condition (K_r), ocean temperature, and chlorophyll-*a*. The GAMM edf = model estimated degrees of freedom, AIC = Akaike information criterion, ΔAIC = AIC difference, the deviance explained is a pseudo R^2 statistic.

Model	edf	AIC	ΔAIC	Deviance explained
base + Kr + summer temp	136.8	1732.8	0.00	78.5
base + Kr + summer temp + chl-a	134.7	1733.4	0.53	78.5
base + Kr + winter temp	136.1	1735.6	2.71	78.5
base + Kr + winter temp + chl-*a*	132.4	1736.0	3.19	78.4
base + Kr	129.9	1766.3	33.17	78.6
base + chl-*a*	135.4	1882.9	150.02	76.4
base	130.4	1908.0	175.19	76.3
base + summer temp	132.4	1909.5	176.69	76.4
base + STI duration	105.6	1911.3	178.50	76.3
base + winter temp	123.2	1913.1	180.32	76.3

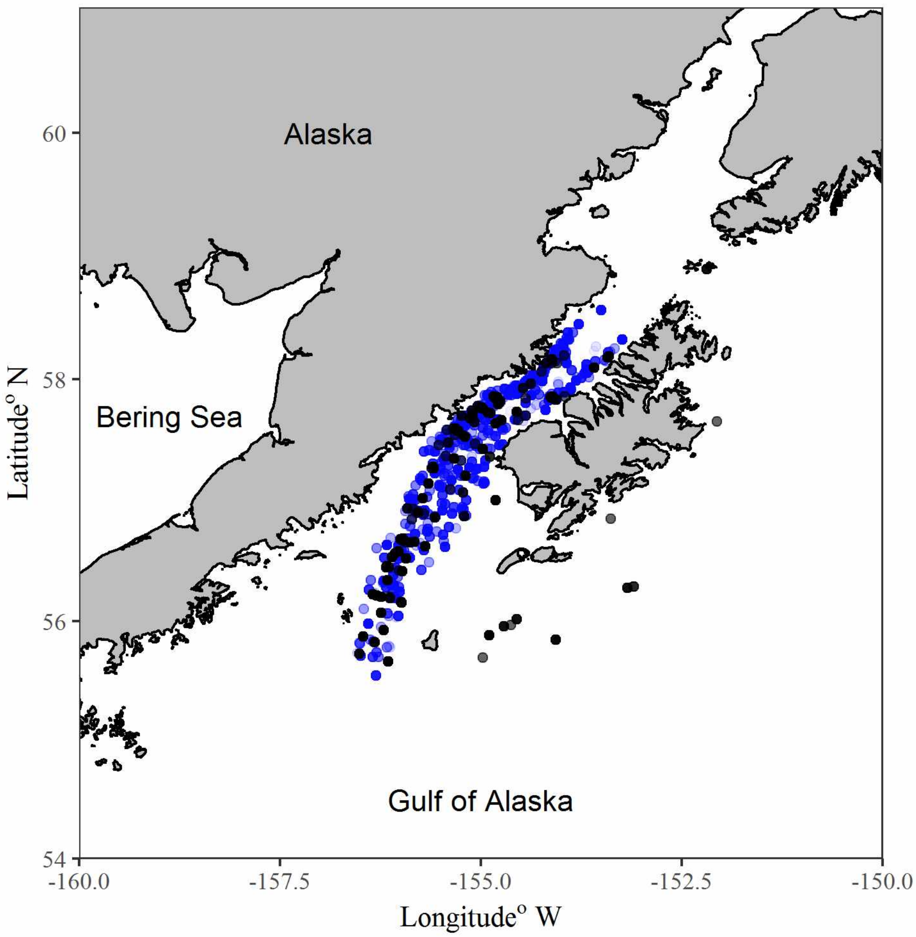

Figure 3.1. Map of Shelikof Strait with associated pollock maturity and fecundity sampling locations. Each point is a sample location, maturity samples are blue, fecundity samples are black.

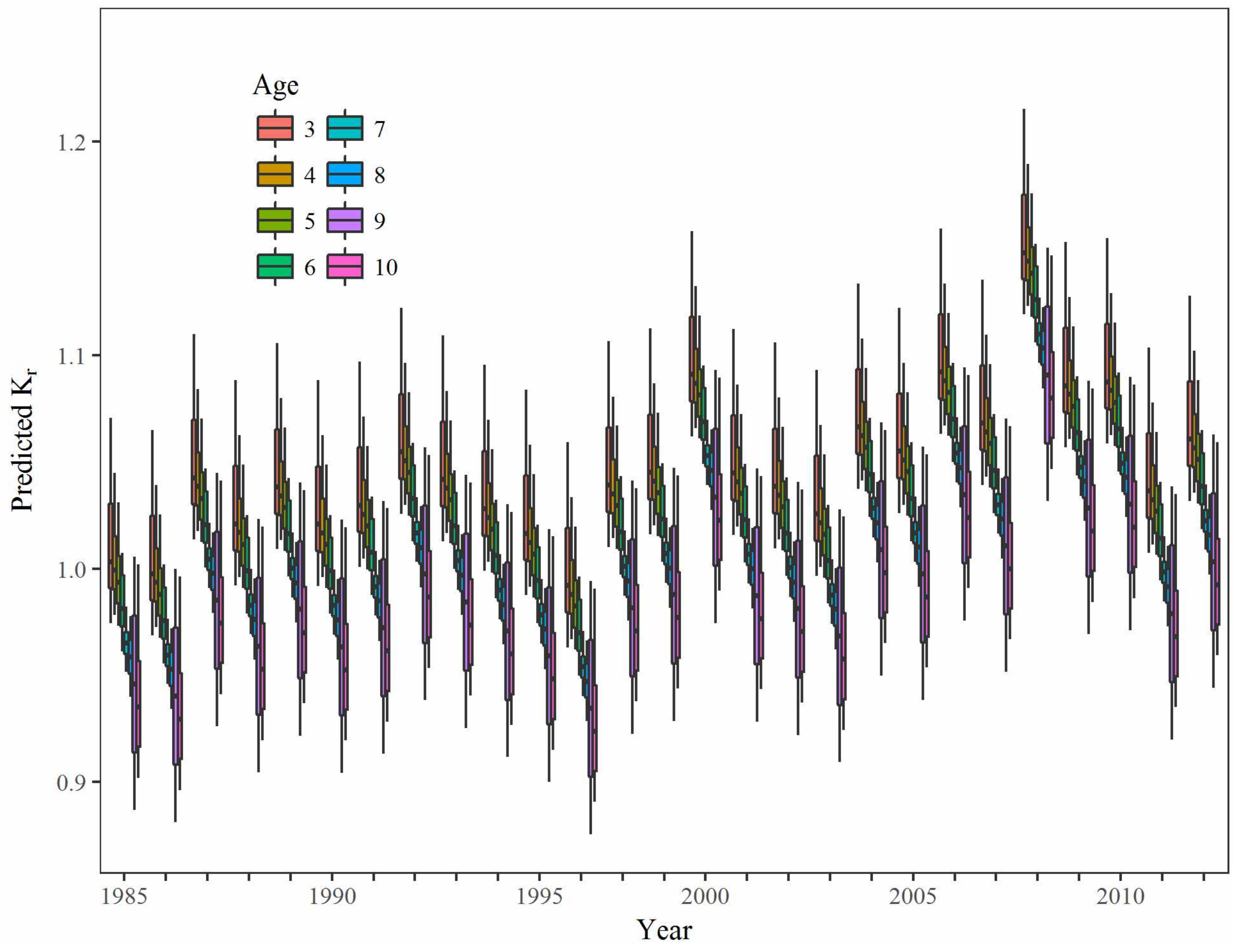

Figure 3.2. Predicted female pollock body condition (K_r) from the GAMM after accounting for the effects of cohort abundance by age, length, age, year, maturity status (immature/mature), and the haul from which an individual was sampled. Boxplots display the median, 25^{th} and 75^{th} quartiles, minimum and maximum values.

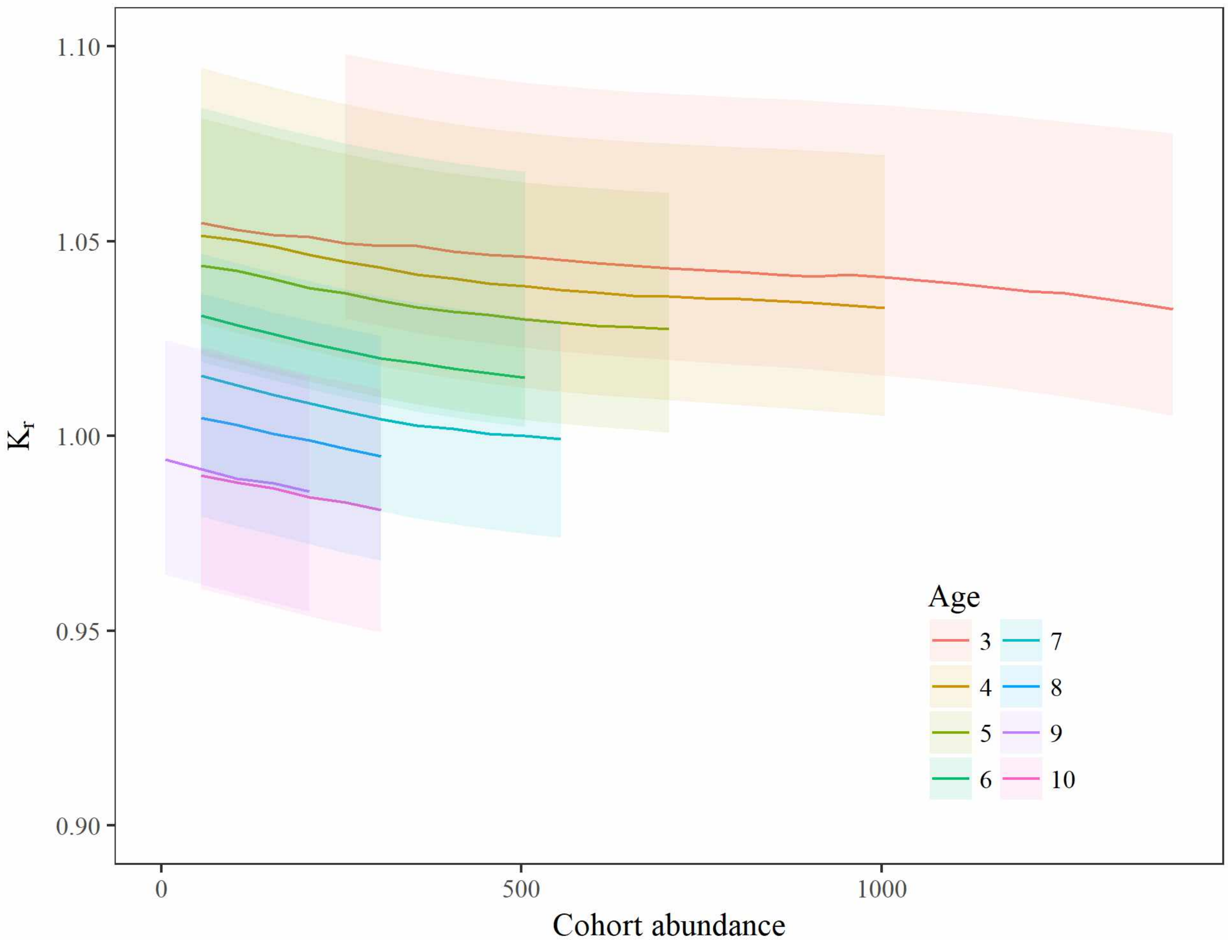

Figure 3.3. Female pollock body condition (K_r) GAMM predicted response to cohort population abundance by age after accounting for the effects of length, age, year, maturity status (immature/mature), and the haul from which an individual was sampled (Equation 3.4). Shaded areas are 90% confidence intervals.

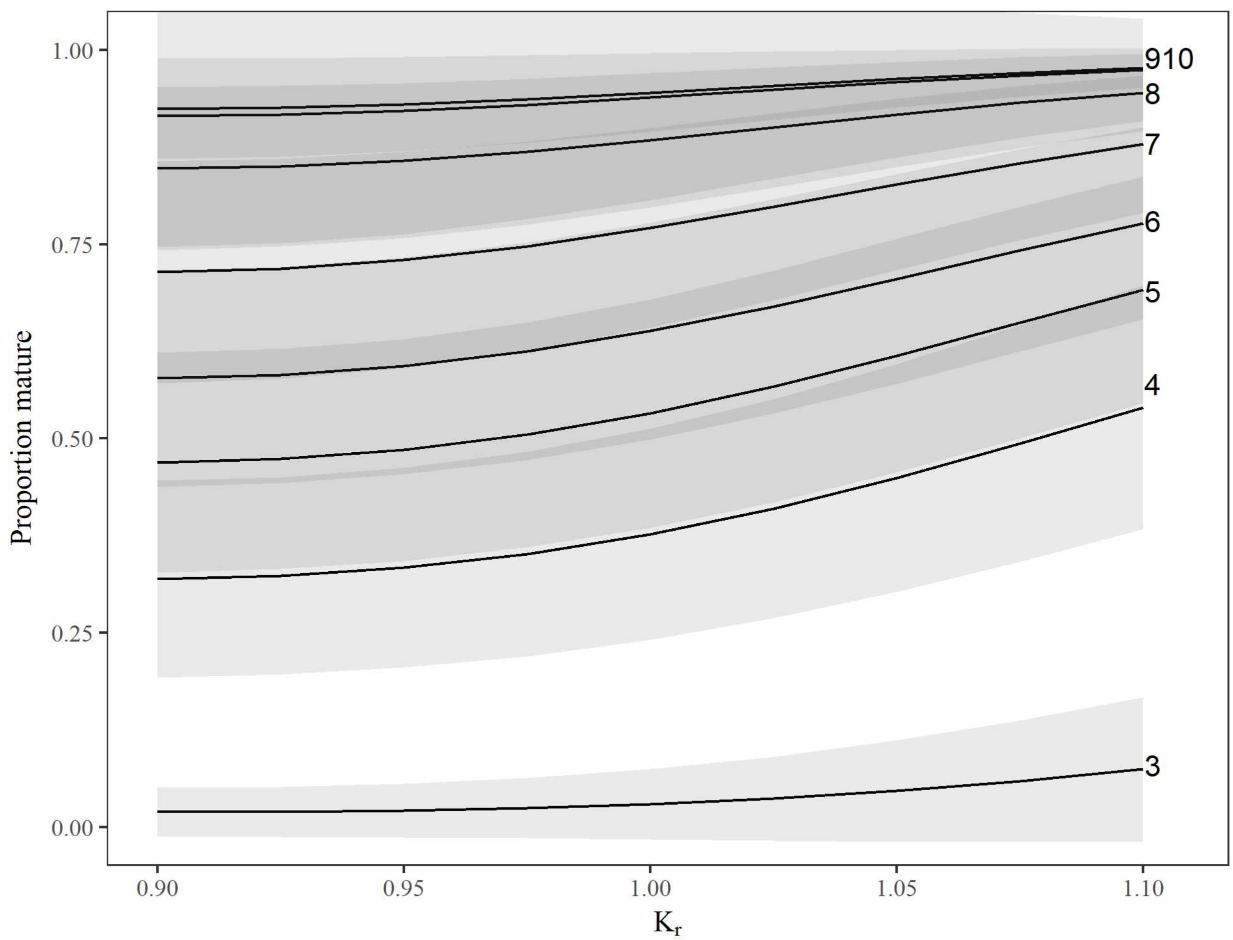

Figure 3.4. The predicted proportion of mature female pollock, by age, relative to body condition (K_r) from the GAMM after accounting for the effects of length, location, year, and the haul from which an individual was sampled. Numbers indicate the age-class; shaded areas are 95% confidence intervals.

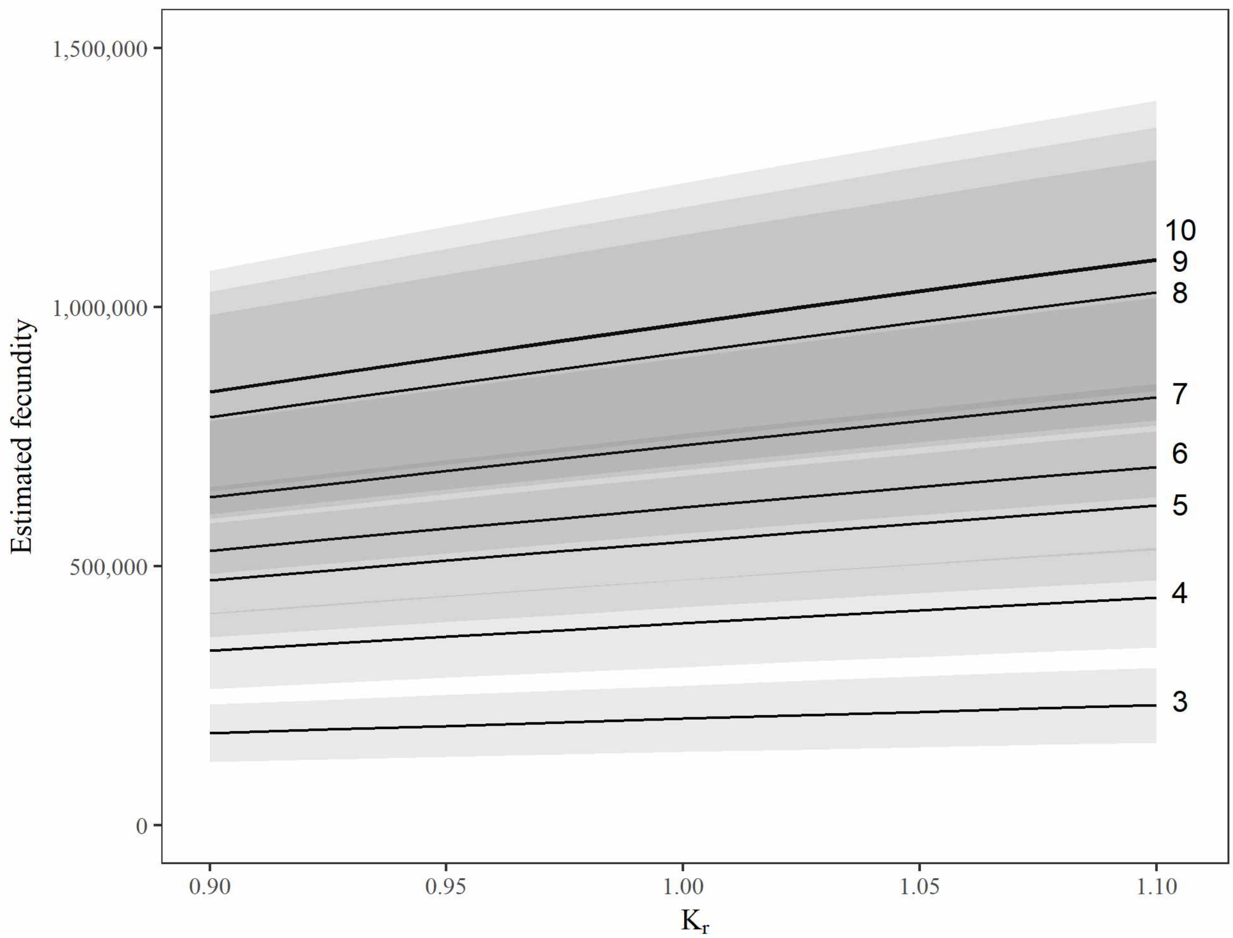

Figure 3.5. The predicted influence of body condition (K_r) from the GAMM on estimated total fecundity of mature female pollock after accounting for the effects of length, egg diameter, the haul from which an individual was sampled, and ocean temperature. Numbers indicate the age-class; shaded areas are 95% confidence intervals.

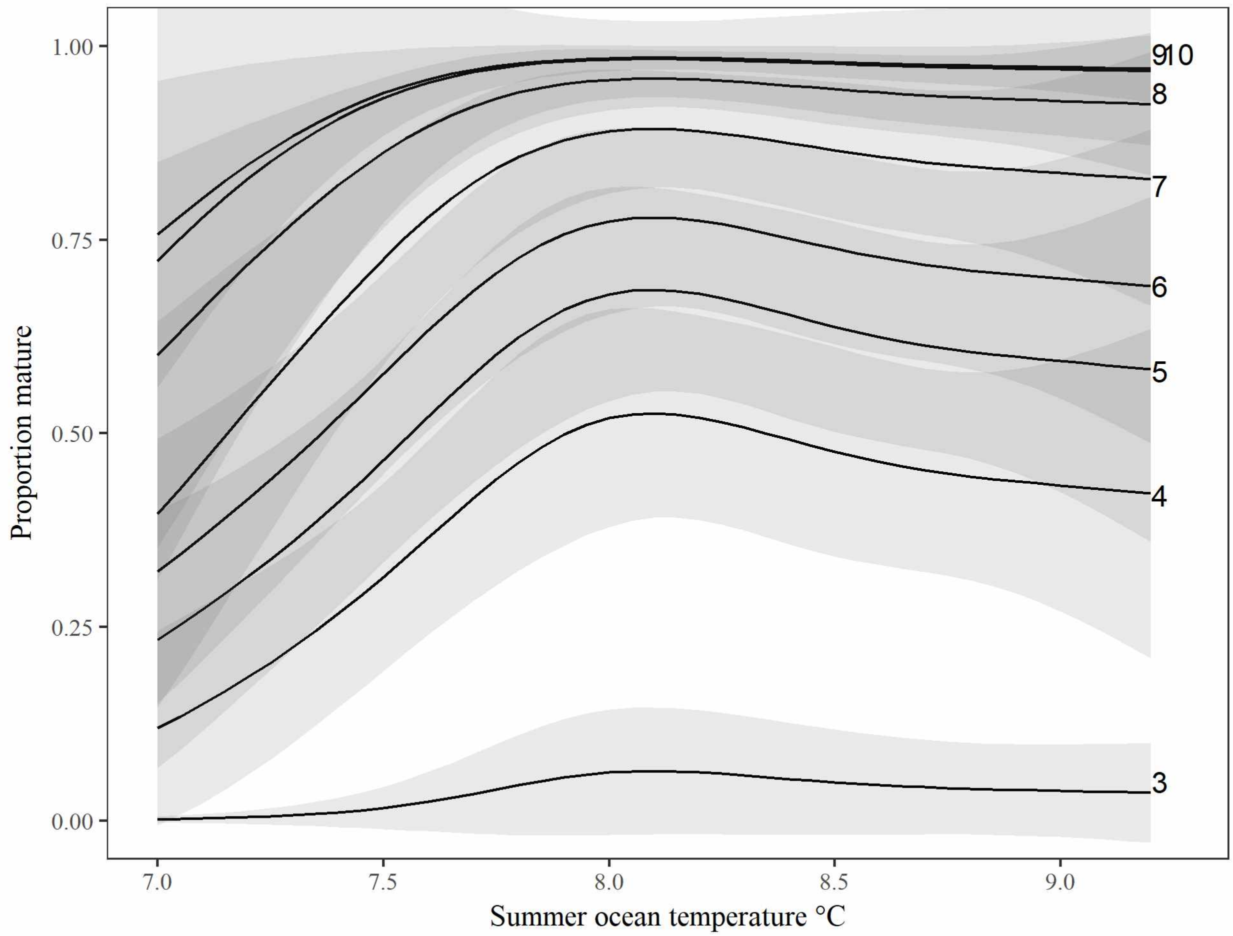

Figure 3.6. The predicted influence of depth-integrated summer temperature from the GAMM on female pollock maturity estimates after accounting for the effects of length, egg diameter, the haul from which an individual was sampled, and body condition (K_r) and chlorophyll-*a*. Numbers indicate the age-class; shaded areas are 95% confidence intervals.

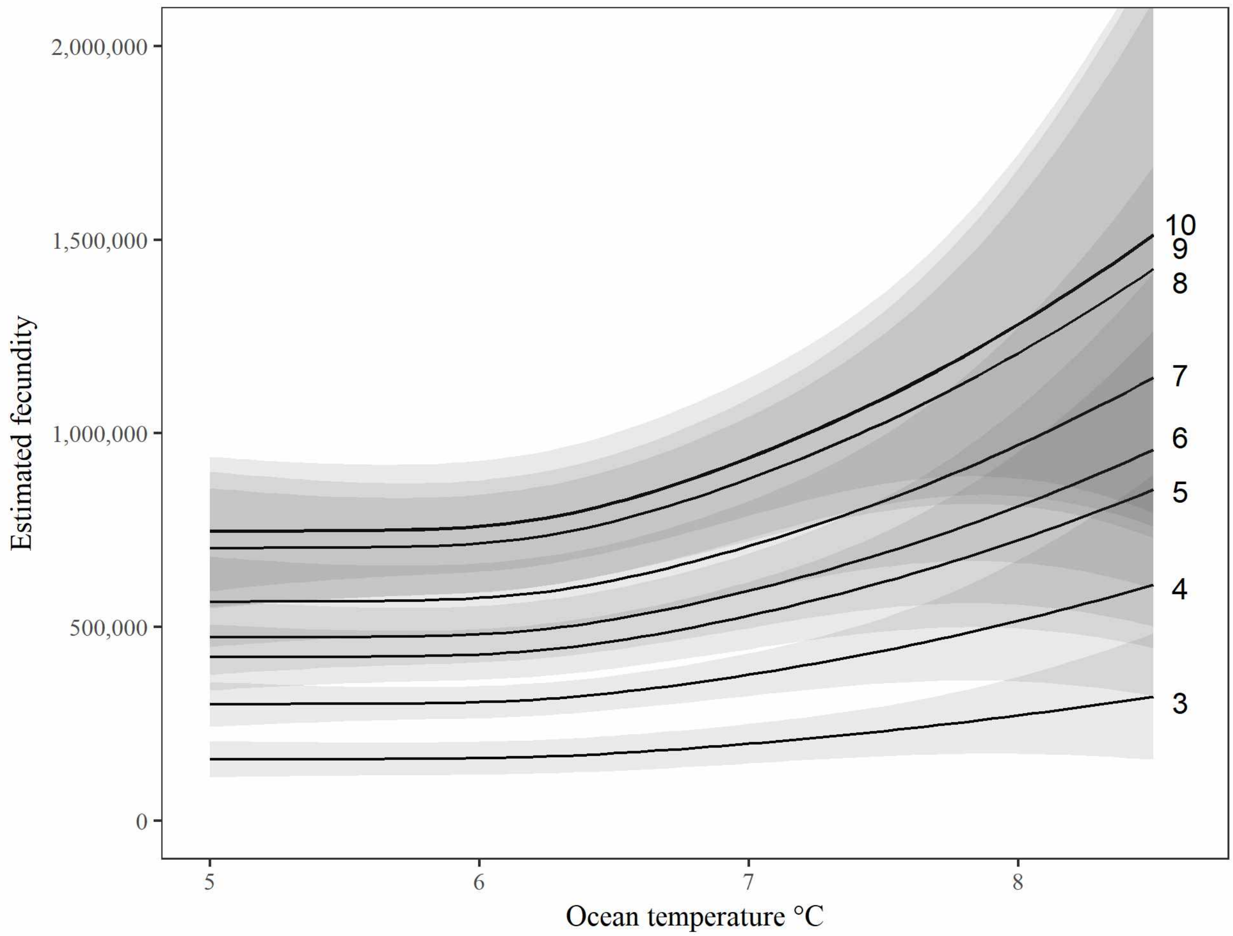

Figure 3.7. The predicted influence of depth-integrated winter temperature from the GAMM on female pollock fecundity estimates after accounting for the effects of length, egg diameter, the haul from which an individual was sampled, and body condition (K_r) and chlorophyll-*a*. Numbers indicate the age-class; shaded areas are 95% confidence intervals.

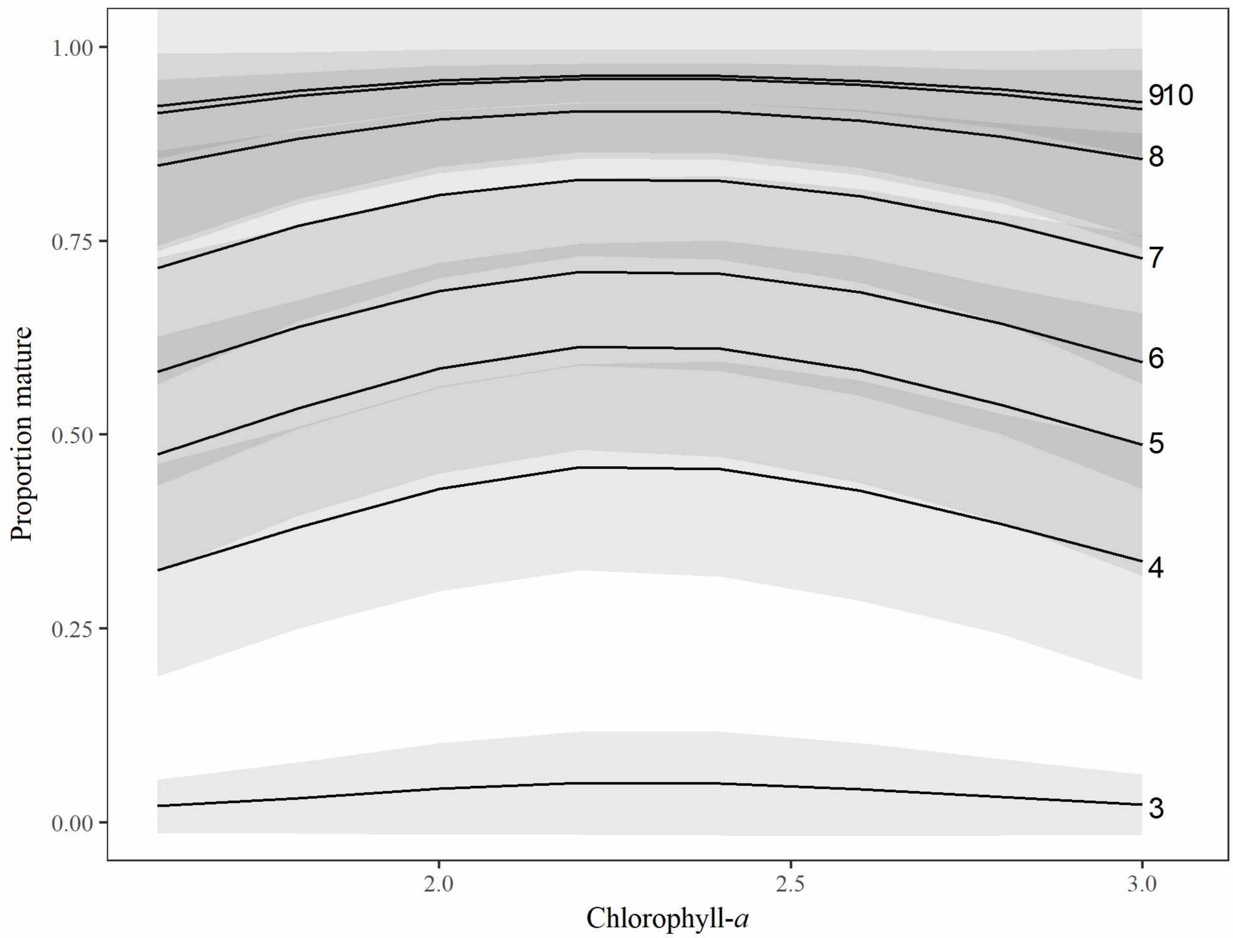

Figure 3.8. The predicted influence of chlorophyll-*a* from the GAMM on female pollock maturity after accounting for the effects of length, location, year, the haul from which an individual was sampled body condition (K_r) and summer ocean temperature. Numbers indicate the age-class; shaded areas are 95% confidence intervals.

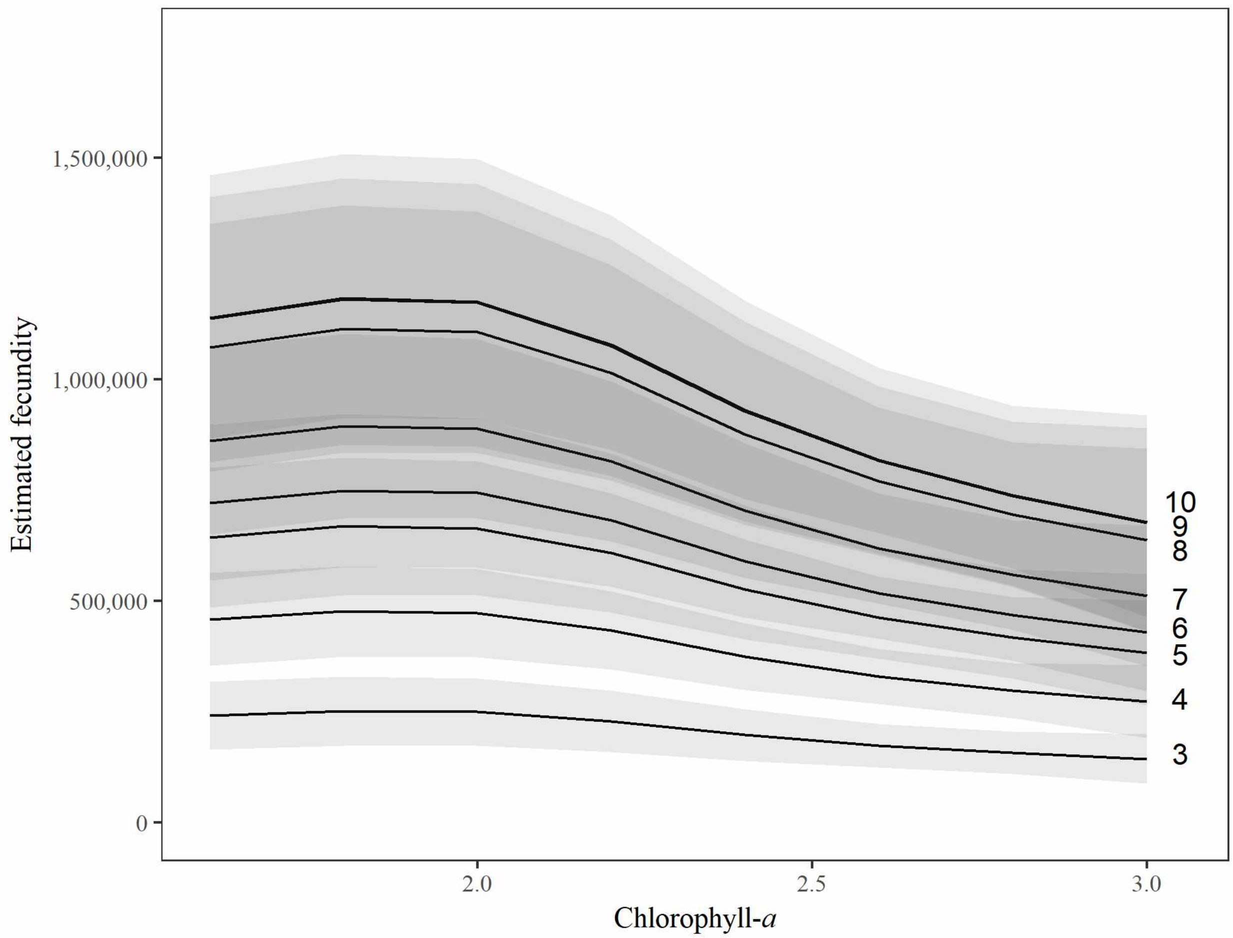

Figure 3.9. The predicted influence of chlorophyll-a from the GAMM on female pollock fecundity after accounting for the effects of length, location, year, the haul from which an individual was sampled body condition (K_r) and winter ocean temperature. Numbers indicate the age-class; shaded areas are 95% confidence intervals.

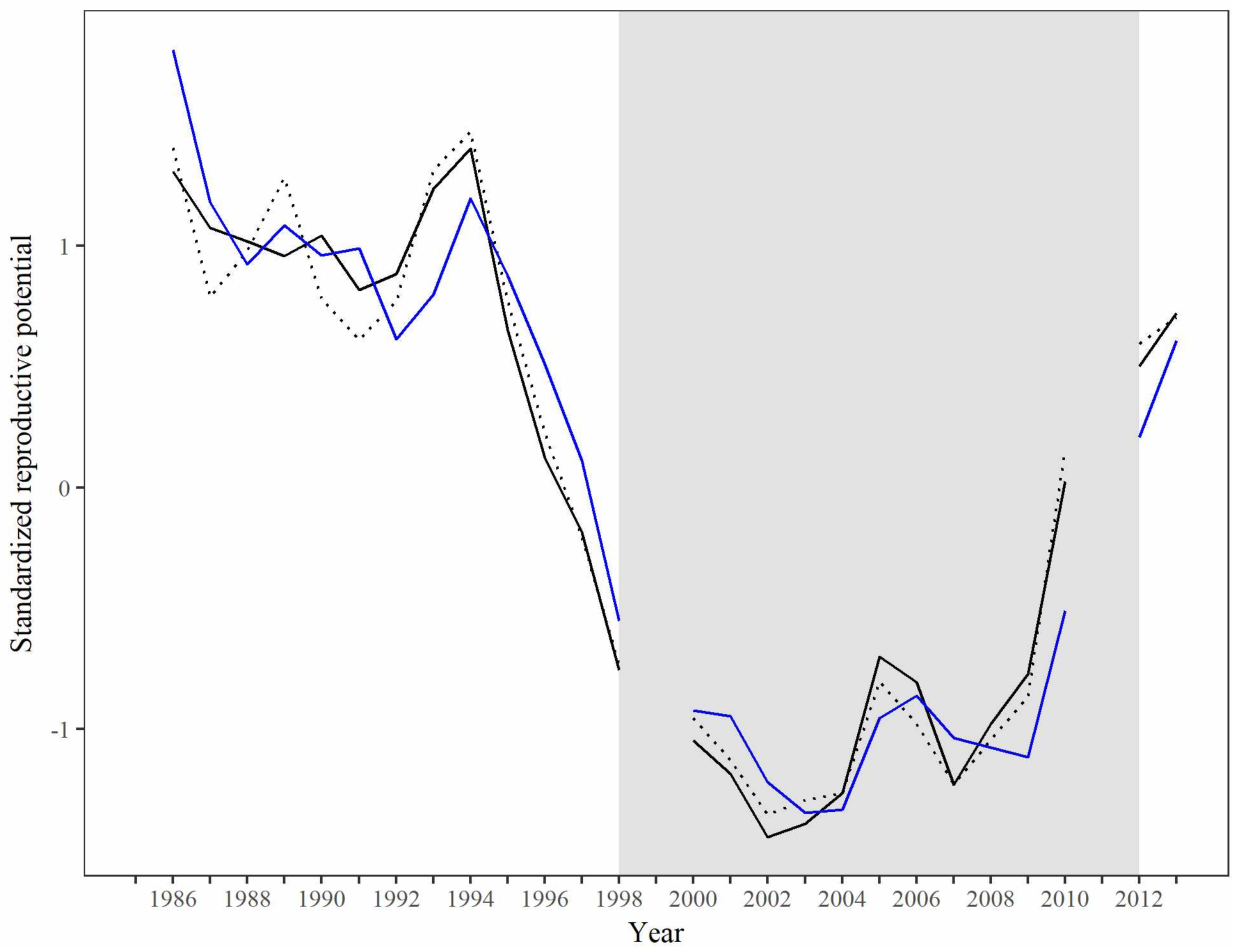

Figure 3.10. Three estimates of annual pollock reproductive potential. The black line is total egg production as estimated from the top fecundity and maturity models described in this paper, the blue line is the stock assessment estimate of spawning stock biomass based upon average maturity at age; the dotted line is an estimate of spawning stock biomass based upon time varying maturity. In the gray shaded area predictions were based upon observed values of ocean temperature, K_r, and chlorophyll-*a*, outside of the shaded area, median environmental and body condition values were used for GAMM prediction.

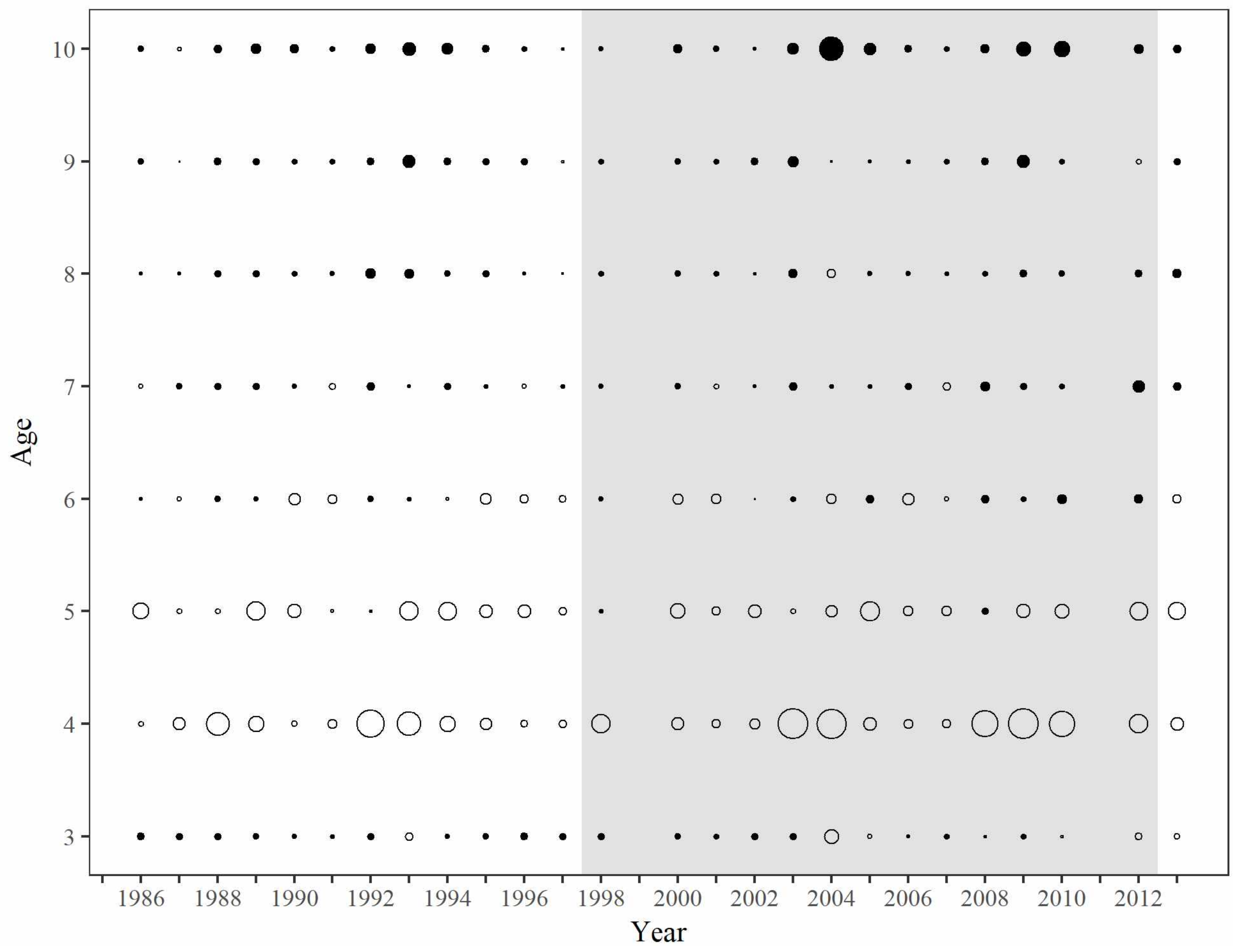

Figure 3.11. Residual plot of differences between standardized reproductive potential by age and year. Filled circles are positive residuals (spawning stock biomass - total egg production), open circles are negative residuals. The size of the circle indicates the relative magnitude of the residual effect. In the gray shaded area predictions were based upon observed values of ocean temperature, K_r, and chlorophyll-*a*, outside of the shaded area, median environmental and body condition values were used for GAMM prediction.

Chapter 4

An agent-based model to examine parallel and divergent fishery management strategies for transboundary stock: application to the walleye pollock fishery in the Gulf of Alaska[I]

4.1 Abstract

Fisheries managers employ a suite of management strategies and measures to promote long-term social and economic benefits while preserving the productive capacity of fish stocks. However, for cases in which stocks straddle fishery jurisdictions, legal, social, and/or political considerations may prevent adoption of coherent management strategies. Lack of consistent management can adversely affect sustainability of transboundary stocks and thus reduce long-term social benefits. As a case study for straddling stocks, we used an agent-based model to examine a suite of available federal and state management strategies as they relate to the economic viability of a nascent Alaska state-waters trawl fishery for walleye pollock (*Gadus chalcogrammus*) that may develop after a long history of parallel state and federal waters management. Results of alternative strategies were compared in terms of indicators, such as variance of catch and quasi-rent value. Given the input characteristics of these simulations, the management strategy that produces the best overall improvements relative to status quo involved a federal-waters management strategy that allows for community-based cooperatives and an open access strategy in state waters. Agent-based models of the type we have developed may be used to inform managers of the underlying dynamics of catches and revenues in order to avoid unintended consequences of management decisions and to improve the likelihood of attaining fishery management objectives.

4.2 Introduction

Because fish stocks often straddle state, national, and international boundaries, there is a need to coordinate fishery management across jurisdictions. This is best achieved when management objectives and strategies align and there is coordinated decision-making and catch accounting among jurisdictions. However, when legal, social, or political considerations lead to differences in management objectives or management strategies it can be difficult to coordinate decision-making (Munro, 1991; Scholtens and Bavinck, 2014). Even in such cases of divergent management, certain combinations of management strategies increase the likelihood of achieving the management objectives of each jurisdiction over other permutations.

One approach to quantifying management scenario outcomes is agent-based modeling (ABM). ABMs are "bottom-up simulation models" (Lamberson, 2002) that simulate the actions of "agents"

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(i.e., individuals or groups) with defined behaviors that may interact with each other and their environment (Gilbert, 2008). Each agent is governed by simple rules that respond to the environment in a particular fashion, given the location of the agent within the environment. The environment can be designed to represent the real world or some stylized version thereof (i.e., virtual world) and may be designed to be spatially explicit. Such models are commonly used in ecology, where they are often referred to as individual-based models (Grimm et al., 2005).

Many types of ABMs have been successfully developed to examine ecological, social or socio-ecological systems (Grimm et al., 2010). Some ABMs explore biological relationships such as moth infestations and controls (Vuuren et al., 2017), or the effects of size-selectivity on salmon population characteristics (Bromaghin et al., 2011). Other ABMs have been used to explore fishing fleet dynamics (Holland and Sutinen, 1999) and fishery stability (Helu et al., 1999).

In this study we explored the utility of ABMs by exploring the implications of parallel and divergent management strategies in a system where a fish stock straddles jurisdictional boundaries. Our model incorporates relevant biological, social, and economic factors to simulate the trade-offs and implications of alternate management strategies, while allowing determination of economically optimal management approaches at the community level. For illustration, we parameterized our model to reflect stylized aspects of state and federal fisheries for walleye pollock (*Gadus chalcogrammus*; hereafter pollock) in the Gulf of Alaska (GOA).

The GOA pollock fishery is currently managed under a License Limitation Program (LLP) in federal waters (3-200 nmi offshore) and as a parallel open access fishery in state waters (0-3 nmi offshore). In managing the parallel pollock fishery, the State of Alaska has adopted most federal rules and regulations in state waters with the exception of the LLP. In federal waters, the North Pacific Fishery Management Council (Council) has been exploring alternatives to LLP management as a means of reducing the incidental catch of prohibited species (Pacific salmon *Oncorhynchus* spp. and Pacific halibut *Hippoglossus stenolepis*) in the fishery (Witherell et al., 2000; DiCosimo et al., 2015).

Meanwhile, in state waters, the Alaska Board of Fisheries (BOF) has considered changes to regulations for this fishery to expand economic opportunity for coastal communities adjacent to the fishing grounds. Some management strategies available for Council consideration in federal waters are not legally viable in state waters. Similarly, some of the management objectives that the BOF could consider for fisheries in state waters cannot serve as a basis for selection of management strategies for corresponding fisheries in federal waters. For example, the Council could adopt a management strategy that distributes exclusive durable shares of the total allowable catch (TAC) to fleet sectors and/or community-based entities. However, the Alaska Supreme Court has found that, with few exceptions, Article VIII of the Alaska State Constitution bans state resource management agencies from issuing exclusive entitlements to shares of common-property fishery resources. Although the Court has found that limited entry and super-exclusive registration are not prohibited by Alaska's state constitution (Alaska Supreme Court., 1980), the Court has generally sided with challenges to more comprehensive forms of rights-based management, such as the Chignik Cooperative (see Alaska Supreme Court., 2005, 2006; Knapp, 2008; Criddle and Shimizu, 2014). The Chignik Cooperative was a salmon purse seine cooperative fishery instituted in 2002 by the BOF at the request of permit holders. Several sectors of federally managed fisheries in Alaska have the option to develop fishing cooperatives. This unique state-waters cooperative was contested and the Alaska Supreme Court ended the cooperative when they ruled in 2006 that permit holders must operate their own vessel (Knapp, 2008). Nevertheless, the Court has allowed an equal quota share management system in state waters in the Southern Southeast Inside and Prince William Sound sub-district sablefish (*Anoplopoma fimbria*) fisheries. Thus, there is very limited precedent for individual fishing quotas (IFQs), sector allocations (cooperatives), or community quotas (CQs) in state waters. Consequently, if the Council adopts an unequal catch-share system for the GOA pollock fishery in federal waters based on individual fishing histories, it is highly unlikely that the state would be able to adopt a parallel management strategy in state waters.

Stakeholder interest in developing new fisheries in state waters led to submission of a proposal to the BOF in 2013 to establish a state-managed pollock fishery in state waters of the GOA. Proposal 44-5 AAC 28.36X, if approved, would have allocated 25% of the combined TAC from federal reporting areas 620, 630, and 640 to state waters in the Prince William Sound (PWS, state fishery management area E), Cook Inlet (CKI, area H), Kodiak (KOD, area K), and Chignik (CHG, area L) state management areas (Figure 4.1). Similarly, under this plan, 25% of the TAC for federal reporting area 610 would have been allocated to the state's Southeast Peninsula management area (SOP, area M). The impetus for Proposal 44-5 was to maintain open access harvesting opportunities for pollock in state waters given concerns about a potential share-based access program in federal waters. Proposal 44-5 included limits on vessel size, gear type, duration between landings, and maximum delivered weight per landing; these provisions were intended to extend benefits to fishers on small vessels that are mostly home-ported in coastal communities. The BOF established a "Pollock Workgroup" to consider whether and how a state fishery managed using a Guideline Harvest Level (GHL, state of Alaska's equivalent to a federal catch quota) would enable the Alaska Department of Fish and Game to "manage, protect, maintain, improve, and extend the fish…resources of the state in the interest of the economy and general well-being of the state" (Title XVI of the Alaska Constitution). While the Pollock Workgroup completed its work in July

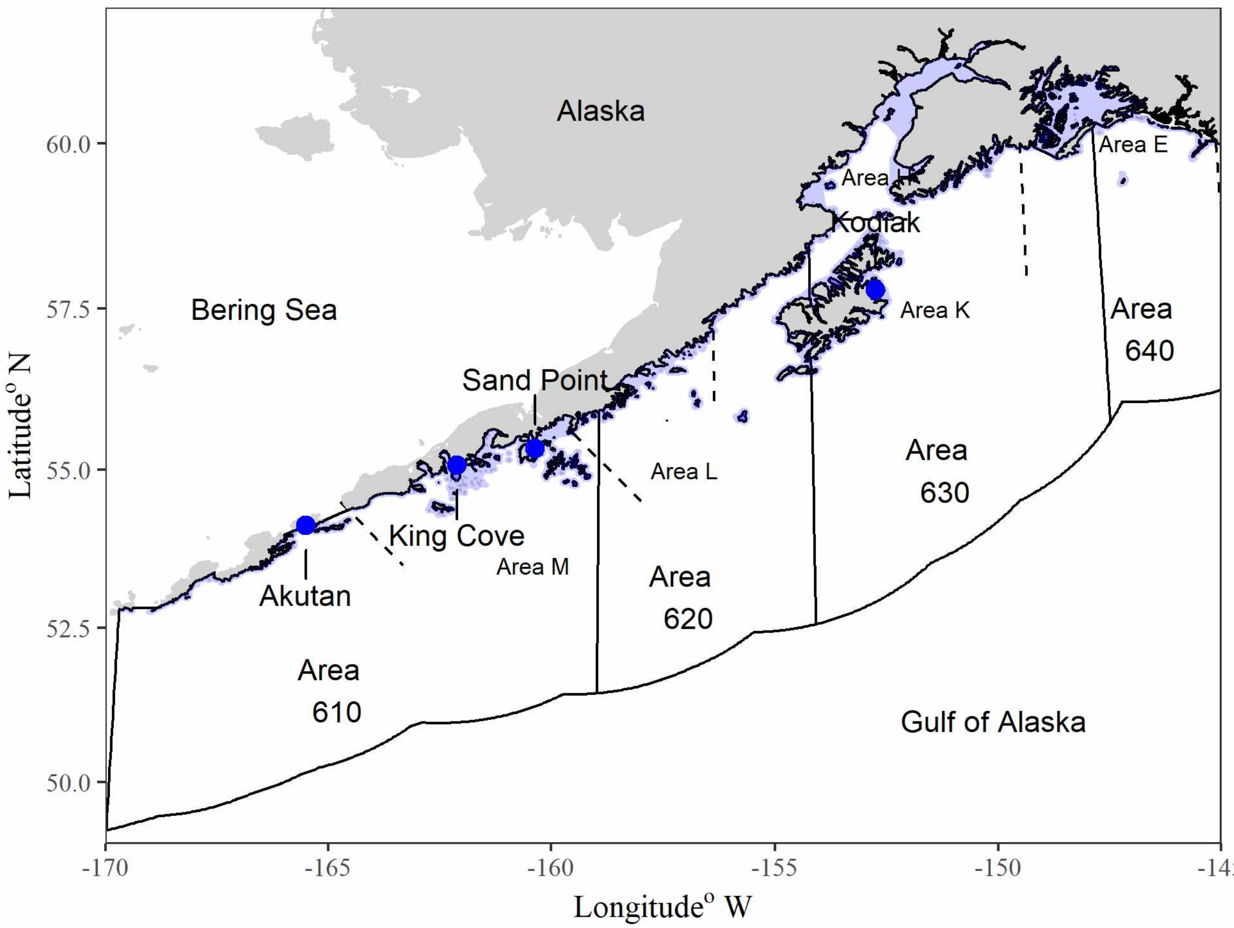

Figure 4.1. Map of state and federal fishing areas in the Gulf of Alaska. State waters, 0-3 nmi, are shaded blue with lettered management areas; federal management authority extends from 3-200 nmi from shore. Federal management Areas 630, 620, and 610 were included in the model as areas 1, 2, and 3, respectively. Area 640 was not considered. The fishing ports of Kodiak, Sand Point, King Cove, and Akutan, were included in the model as port 1, 2, 3, and 4, respectively.

2015, the BOF took no action on Proposal 44-5. Nevertheless, there remains stakeholder interest and the BOF continues to consider options for changes to statewide pollock fisheries.

Because management actions adopted by the Council may create spillover effects into state-water fisheries and vice versa, the Council's and BOF's preferred management alternative may depend on what measures are adopted by their counterpart. Additionally, adoption of new strategies to address management concerns may have unintended consequences. Proposals such as Proposal 44-5 arise from a wish to create opportunity for new entrants with small vessels in state waters, but that opportunity would come at a cost of reduced opportunity for current participants, such as those with large fishing vessels. Conversely, federal catch-share programs may be beneficial to many current participants and provide for better control of harvest (Hannesson, 1996; Wilen, 2005; Branch, 2009; Criddle, 2012), but they may decrease the resilience of fishery-dependent communities and fishing operations that have limited catch history, such as small vessels (Adasiak, 1979; Copes and Charles, 2004; McCay, 2004; Lowe, 2008; Carothers, 2010; Criddle, 2012; Himes-Cornell and Hoelting, 2015). It is preferable to examine potential effects of management strategies prior to implementation so that managers are informed about the trade-offs and consequences of alternative decisions. Indeed, recent research has shown that understanding the impacts of policy changes in fisheries management requires a thorough comprehension, derived in part through modeling, of the underlying technological structure of the fishery and responses to both market and institutional constraints (Reimer et al., 2017). The objectives of this study are to: (1) develop an ABM that uses a discrete, static, stochastic simulation-optimization framework to estimate the local economic impacts of combinations of federal and state management strategies, and (2) compare the simulated economic outcomes of the management strategies across stock levels consistent with recent (1998 - 2015) fishery history. We employed the ABM to examine four federal management strategies (IFQs, catch-share allocations to community fishing associations, LLPs with the ability to form cooperatives, and bycatch/prohibited species catch (PSC) allocations) in combination with four state management strategies (open access, limited entry, limited entry with super-exclusive registration (Natcher et al., 1996), and limited entry with equal catch shares (Table 4.1). For comparison, we also evaluated a status-quo (no action) strategy. We anticipated that each combination of management strategies would have different impacts on individual fishers and fishery-dependent communities.

4.3 Materials and methods

4.3.1 Overview

We developed an ABM to examine the effects of various combinations of alternative federal and state strategies to manage GOA pollock on estimated vessel revenues by community. A commonly occurring question for fishery managers is how management actions will affect communities in terms of fishery participation, changes in revenue streams, or both. This ABM is structured to provide managers with an understanding of underlying fleet dynamics in order to determine how to effectively manage the straddling fisheries.

The agents are individual vessels that behave in response to state variables conditioned on a combination of historical individual participation in the fishery and the specifics of the management scenarios being evaluated. Agent behavior is generalized by season and vessel size-class, using metrics such as historical average catch and trip duration. The model includes federal management areas 630, 620 and 610, denoted in the simulation as areas 1-3, respectively.

The model includes four fishing ports to represent Kodiak, Sand Point, King Cove, and Akutan, denoted in the simulation as ports 1-4, respectively. Kodiak is the largest port in the region with eight shoreside processors in 2015 (Fissel et al., 2016) and annual average groundfish landings of 80% of the GOA delivered volume; the other ports each have one major processor. Annual groundfish landings in Sand Point are about 12% of the GOA delivered volume (Dorn et al., 2016), King Cove, and Akutan have reduced delivery volumes relative to Sand Point, with Akutan having the lowest volume. Accurate catch accounting by port cannot be reported here due to data confidentiality. Each of these ports process groundfish from the GOA and BSAI. Akutan primarily handles landings from the BSAI; Kodiak primarily handles landings from the GOA, Sand Point and King Cove mostly handle groundfish from the GOA but include substantial amounts of BSAI groundfish. The four fishing seasons represented in the model each had a duration as established in management regulation: A season: January 20 – March 10, B season: March 10 – May 30, C season: August 25 – October 1, and D season: October 1 – November 1 (https://alaskafisheries.noaa.gov/sites/default/files/15_16goatable4.pdf). The four vessel size-classes represented in the model were based upon the Alaska Commercial Fisheries Entry Commission (CFEC) fishery codes (https://www.cfec.state.ak.us/misc/FshyDesC.htm) for otter trawl vessels (<18.2 m, 18.2-27.3 m, 24.4-38.1 m, and >38.1 m). Agents are assumed to select where they fish during each trip to maximize anticipated revenue. Fishing areas are closed once the seasonal IFQ, TAC, or PSC for that area has been reached. All areas are closed to fishing when the duration of a season has been reached.

4.3.2 Process overview

When an ABM simulation is initialized all vessels begin fishing. The time step advances by a day through the course of a season. The probability that a vessel participates on a given day is based upon the average historical participation of a vessel during a given season. State variables, such as season length, TAC, anticipated ex-vessel price, and expected fuel price, are defined at the start of each simulation and invariant through time. The number of days remaining in a season and available TAC remaining for a given area/vessel are decremented throughout the course of a season. The general decision matrix for each agent is shown in Figure 4.2. Each agent originates from a port, if the season is open, there is TAC available (area dependent), and bycatch/PSC quota is either not a management option or bycatch/PSC quota is available, a grid search routine is performed. The grid search is based upon the assumed catch, catch rate, ex-vessel value and fuel price. The output of the grid search informs an agent of the area to fish and the port of delivery. This cycle is repeated until either the season is closed, all of the TAC in all areas available to be fished has been caught, or the bycatch/PSC quota, if relevant, has been reached.

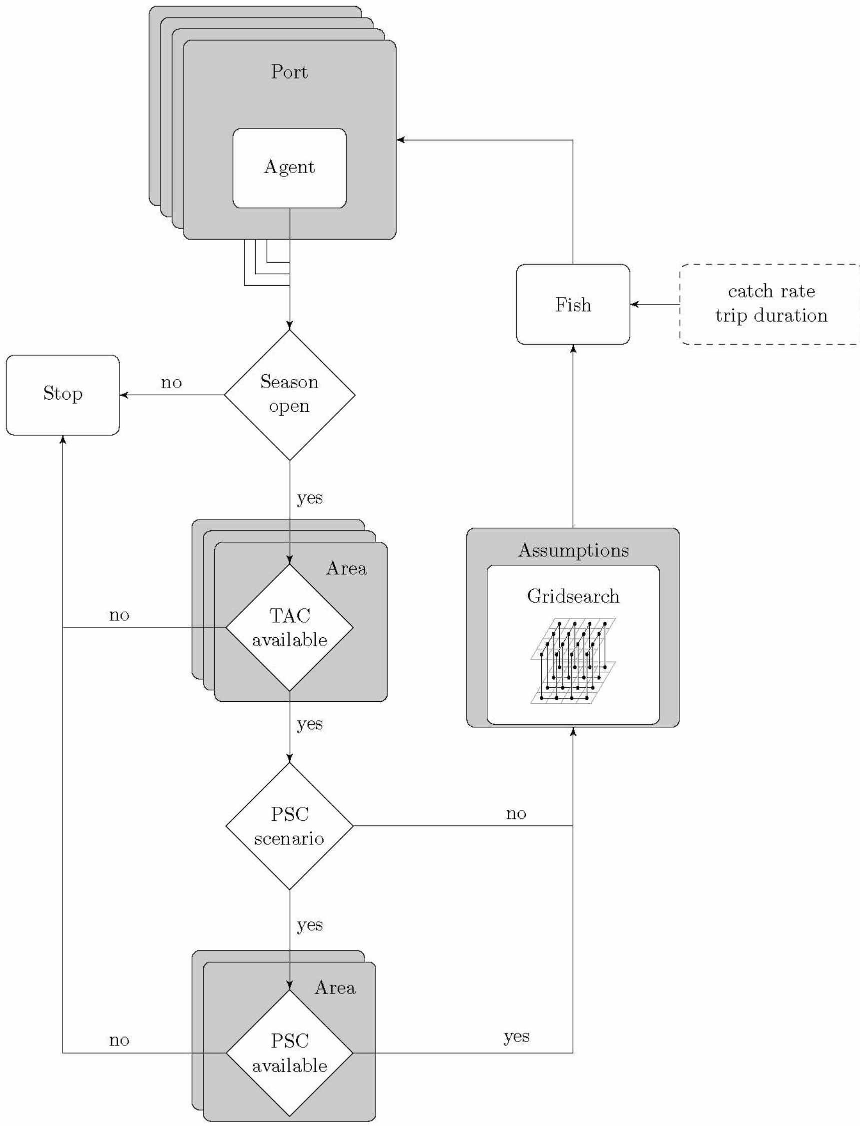

Figure 4.2. Agent-based model diagram. Each agent originates from a port, checks whether the season is open, whether TAC is available (area dependent) and whether bycatch/PSC quota part of the current management routine and if so whether quota is available. A grid search routine is based upon user inputs of assumed catch, catch rate, ex-vessel value and fuel price with the output informing an agent of the area to fish and the port of delivery. This cycle is repeated until either the season is closed, all of the TAC in all areas has been caught, or the PSC quota, if relevant, has been reached.

4.3.3 Design concepts

Each agent is assumed to select a fishing strategy that maximizes their expected net revenue. Revenue optimization is performed via discrete optimization (e.g., grid search routine) as all of the state variables are integers. Catch and quasi-rent (short-term net revenues) vary depending upon the management strategy implemented. The model is structured so that substantive differences in total catch and revenue by port are due to changes in management strategy rather than changes in individual behavior. Agents may not adapt behavior over time, but may change behavior between management strategies. Specifically, individual behavior includes stochasticity, but the underlying behavior is consistent. Agents are only capable of "sensing" ex-vessel price, anticipated trip durations, and fuel costs; they may join a cooperative and allocate their quota to another vessel in a cooperative type scenario. Agents have been designed to have limited and restricted interactions, with the only meaningful interaction being cessation of fishing due to the completion of a season or after all quota has been harvested.

Several elements in the model are stochastic. For each trip, a binomial draw determines a vessel's participation on a given day of a season, with a probability based upon past activity. Each vessel was assigned a truncated normal (or truncated lognormal in the case of the smallest vessel size-class) distribution draw of catch based upon port, season, and individual catch history. Similarly, the duration of a trip was drawn from a truncated normal distribution of previous trip lengths by port, season, and individual. Trip duration was considered independent of vessel catch per trip. These stochastic elements were utilized to produce variability in processes within the model to reflect inherent variability of the social-ecological fishery system.

Collectives, or groups, of agents may form that have similar behavior, e.g., small vessels may have state waters quota only, while larger vessels have federal quota or a collective of vessels may have quota for only a specific area. Collectives are a key component of some of the management strategies and are anticipated to substantively affect results.

4.3.4 Initialization & Input data

The number of vessels for a métier, a grouping of similar vessels, in a given season and port who fish in a particular area is based upon historical data collected by the CFEC. A vessel's starting or "home" port of call was designated as the average starting port for the first trip of each season over 2006-2014. In the model initial determination of the area where a vessel fished was based upon a grid search routine that optimizes anticipated revenues based upon expected ex-vessel and fuel prices, as well as expected catch and trip duration. If the management scenario being examined did not allow a vessel the flexibility to fish in multiple areas, then the location was determined by the scenario rules.

Submodels

The annual ABC was allocated as a TAC by season and area based upon truncated normal draws, $X \sim N(\mu, \sigma^2)$, $X \in [a,b]$, where μ is the mean allocation and σ is the standard error of the allocations; a and b are the maximum and minimum allocations observed from historical apportionments compiled from Stock Assessment and Fishery Evaluation reports
(https://www.npfmc.org/safe-stock-assessment-and-fishery-evaluation-reports/)
upon which annual federal fishery management decisions are based. The TAC was further divided by area and season with 25% to state waters (as the GHL) and 75% to federal waters in scenarios that designate discrete state and federal water fisheries. It is assumed that pollock biomass is spatially distributed such that there is a sufficiently large enough biomass in each area/fishery to allow the fleet to catch the TAC for that area/fishery. For IFQ allocation the TAC was assigned to each agent based upon individual historical participation in the fishery by season and area (see Appendix B). Scenarios with port (community) allocations had the TAC based upon historical seasonal catch returned to a port from a given fishing area. For equal catch shares in state waters the state TAC was divided equally by the number of vessels participating in state waters by season.

Whether vessel i participated in a fishing trip t during a daily time step was based upon a binomial draw $t \sim B(n, hp)$, where the probability of participation was informed by individual historical participation by season (*hpar*). This was estimated as the annual mean of historical vessel participation from 2006 - 2014:

$$hpar_{i,s} = \bar{t}_{i,s} \frac{\bar{d}_{i,s}}{sl_s}, \tag{4.1}$$

where $\bar{t}_{i,s}$ is the mean number of trips taken by a vessel i in season s, $\bar{d}_{i,s}$ is the average duration of a trip for vessel i in season s, and sl_s is the season length in days.

This ABM was structured so that the i-th agent or vessel in a métier j (vessel size-class) participating during a time step, was assumed to maximize expected short-run profit (NR_i) by choosing where to fish (area $k = 1-3$) and where to deliver their catch (delivery $d = 1-4$) for each trip t based upon their port of origin (port $p = 1-4$). Expected max net revenue for an individual trip was calculated as expected gross revenue minus expected costs:

$$Max(NR_{i,t}) = E(e_i) \cdot E(q_i) - f_1(E(\tau_i), E(o_i)). \tag{4.2}$$

Expected gross revenue was calculated as the product of expected ex-vessel price $E(e)$ and expected catch $E(q)$. Net revenue was calculated by subtracting fuel and observer costs $E(o)$ as a function of expected trip duration $E(\tau)$ and $E(q)$ from the gross revenue. Fuel consumption was estimated, following Tyedmers (2001), using an assigned horsepower by métier (500 hp, 750 hp, 1,000 hp, and 1,500 hp), based upon average horsepower in the Alaska Fisheries Information Network vessel horsepower database (http://www.akfin.org/). Observer costs were specified as 0.0625% of gross revenue per current federal regulations (https://alaskafisheries.noaa.gov/sites/default/files/observerfees.pdf); it was assumed that the BOF would implement an observer program for state waters at the same rate.

Optimization of $Max(NR_i)$ was constrained to preclude solutions where the sum of catches exceeds the TAC for any area during a fishing season and to reflect the attributes (where fishers can fish, where they can deliver, how the TAC is partitioned among métiers, whether fishermen operate under a quota system or fish on a common pool, etc.) of various combinations of federal and state management strategies. Optimization was accomplished using the NMOF package (Schumann 2017) in R v.3.4.2 (R Core Team 2017) using grid search routine:

$$Max(NR_{i,t}) = 0 - arg\ min_{j,k,p,d \in S} f(j,k,p,d), \tag{4.3}$$

where $arg\ min_{j,k,p,d \in S} f(j,k,p,d)$ is defined as

$$(j,k,p,d) \in S \mid \forall (w,x,y,z) \in S : f(j,k,p,d) \leq f(w,x,y,z)$$

Once fishing location and delivery port were determined via optimization a vessel's catch ($q_{i,j,s,t}$) for vessel size classes $j = 2-4$ from area k delivered to port p in season s were treated as stochastic variables drawn from a truncated normal distribution parameterized on historical catches reported to the CFEC, $q \sim N(\mu, \sigma^2), q \in [a,b]$ where the minimum catch was $a = 0$ t and the maximum was $b = 140$ t. The small vessel métier ($j = 1$) had trip catch drawn from a truncated lognormal distribution $ln(q) \sim N(\mu, \sigma^2)$, $q \in [a,b]$ to reflect observed historical catches(see Appendix C). Average variable costs $f_1(\cdot)$ were modeled as a function of métier with trip duration ($\tau_{i,j,s,t}$) drawn from a truncated normal distribution of historical CFEC data observations, $\tau \sim N(\mu, \sigma^2)$, $\tau \in [a,b]$ where $a = 0$ days and b was set at 7 days. Observer costs were calculated as previously described.

After each simulation, the net revenue of a vessel's single trip was calculated as:

$$NR_i = e_{i,t} \cdot q_{i,j,s,t} - f_1(\tau_{i,j,s,t}, o_{i,t}). \tag{4.4}$$

Simulated catch and revenue corresponding to the optimal solutions obtained for each combination of state and federal management strategy were summed by port of delivery, and conditions (i.e., ex-vessel price, fleet size, fuel costs) to initiate characterization of likely regional economic impacts. The projected revenues were expressed by their coefficient of variation and absolute revenue values for each port and condition.

4.3.5 Model performance

Model performance was evaluated based upon whether total catch was similar to observed catch because comparing modeled gross revenue to observed gross revenue is difficult to emulate due to varying market forces and the presence of multiple ex-vessel prices per individual delivery in the CFEC dataset. Three representative years at the beginning, middle, and end of the CFEC dataset (2006, 2010, and 2014) were chosen for examination. Simulated catch was compared by season and by port of delivery using aggregate (2006-2014) average behavior by vessel size-class. To account for stochasticity in the ABM, ten simulations were performed for each year (Appendix C). The TAC for these simulations was based upon the total catch observed in the CFEC dataset for each year. The CFEC catch was used to account for any discrepancies that may exist between the CFEC data and the TAC set by the Council for the years examined. The ABM used for this evaluation reflected the current parallel management structure. This model is not structured to fully capture the variability for a given year, but to describe the general underlying dynamics of the fishery. To this end, the simulation results were examined regarding whether they produced realistic output on a scale similar to observed values.

4.3.6 Case study scenarios

The four federal and four state management strategies examined are summarized in Table 4.1. In addition, five "bounding" scenarios (Table 4.2) were considered; these scenarios were used to examine extreme cases of the available strategies. The bounds were based upon subjective judgment as to whether they represented the outer margin of available management strategies. For example, if IFQ is implemented in federal waters with equal catch shares implemented in state waters then combined these scenarios represent an "extreme" case of share allocation. Six "likely" scenarios (Table 4.2) were simulated; it is anticipated that federal and state managers will choose a combination of strategies for GOA pollock fishery management that is similar to one of these hypothetical pairings based on their historical management decisions for other fisheries. These scenarios were also compared relative to a status quo management scenario (LLP in federal waters,

Table 4.1. Management scenarios considered for simulation analyses.

Federal	State
1. IFQ	A. Open-access
2. Catch-share community allocation	B. Limited entry
3. LLP w/ ability to form cooperatives	C. Limited enrty - super-exclusive
4. Bycatch/prohibited species catch allocations	D. Limited entry - equal catch shares

Table 4.2. Management scenarios presented in this study. See Table 4.1 for federal and state scenario designations, numbers identify federal strategies, and letters identify state strategies. Bounding scenarios are those scenarios that represent the outer margins of available management options. Likely scenarios are strategies that it is anticipated managers would be likely to choose.

Bounding	Likely
1C	2A
1D	2B
3A	2C
4C	3A
4D	3B
	3C

open access in state waters). The status quo model was also used for the model performance examination described previously.

For this simulation the following stipulations were adopted for each scenario (see Appendix B for full descriptions):

1. Vessels were not required to return to their port of origin for delivery, except for IFQ scenarios;
2. Limited entry scenarios in state waters exclude vessels >18.2 m length overall;
3. IFQ scenarios exclude the smallest vessel size class; a vessel needed to catch 100 t per year by fishing area and port of delivery to be allocated IFQ. The fishing behavior of individual permit holders was averaged by port and season;
4. The prohibited species catch limit was set at 25,000 Chinook salmon *Oncorhynchus tshawytscha* with 18,316 allocated to Areas 610 & 620 with a catch rate of 0.66 salmon/ton of pollock and 6,684 allocated to Area 610, with a catch rate of 0.32 salmon/ton of pollock

(see http://npfmc.legistar.com/gateway.aspx?M=F&ID=210f1587-0e38-47fa-af4d-3dcd04edf3ac.pdf).

The LLP scenario was used as the underlying model for this scenario;

5. The scenario corresponding to LLP w/ability to form cooperatives was simulated with 85% of the catch and vessels (randomly drawn from all vessels) included in cooperatives. Vessels in a cooperative had an increased probability of fishing (i.e., the quota was more likely to be caught), whereas vessels outside the cooperative fished per their average fishing behavior. Vessels in the cooperative with marginal profits below the 0.05 quantile of the overall fleet's marginal profits did not participate in the fishery (i.e., other vessels fished their quota).

4.3.7 Case study inputs

Two separate ABC inputs were evaluated. In the first examination the ABC was set at 200,000 t and simulated 40 times for each management scenario to account for stochastic variability in the model and to remove the effect of variable population abundance from the results. The number of simulations was selected as a balance between observed stochasticity during model development and the run time per simulation. The second ABC input was set to a range between 20,000–236,000 t in 6,000 t increments; this range reflected historical variability and was replicated five times to incorporate model stochasticity for each management scenario. The range of ABC values allows for a sensitivity analysis of variable population sizes.

The grid search routine optimized anticipated revenues based upon an expected ex-vessel price of US $ 220/t ($ 0.10/lb.), a fuel price of $ 0.80/l, and an observer cost of 0.065% of gross revenue. The ex-vessel and fuel prices can be varied within the model but were held constant for this analysis. Each vessel started a trip with the assumption that they would harvest 50 t of pollock in 2.5 days of fishing, regardless of vessel size, which seems reasonable given historical average catches by vessel size-class (see Appendix C).

4.4 Results and Discussion

Because this model was not implemented with substantive changes to fisher behavior over time, it is effectively examining the short-term implications of a change in management strategies. Also, given the short-term nature of the projections, these analyses have not been inflation adjusted. Therefore, each simulation was utilized as a replicate. Graphical examinations of model outputs show that the model produces realistic catches on a scale similar to observed values (Figure 4.3; Appendix C).

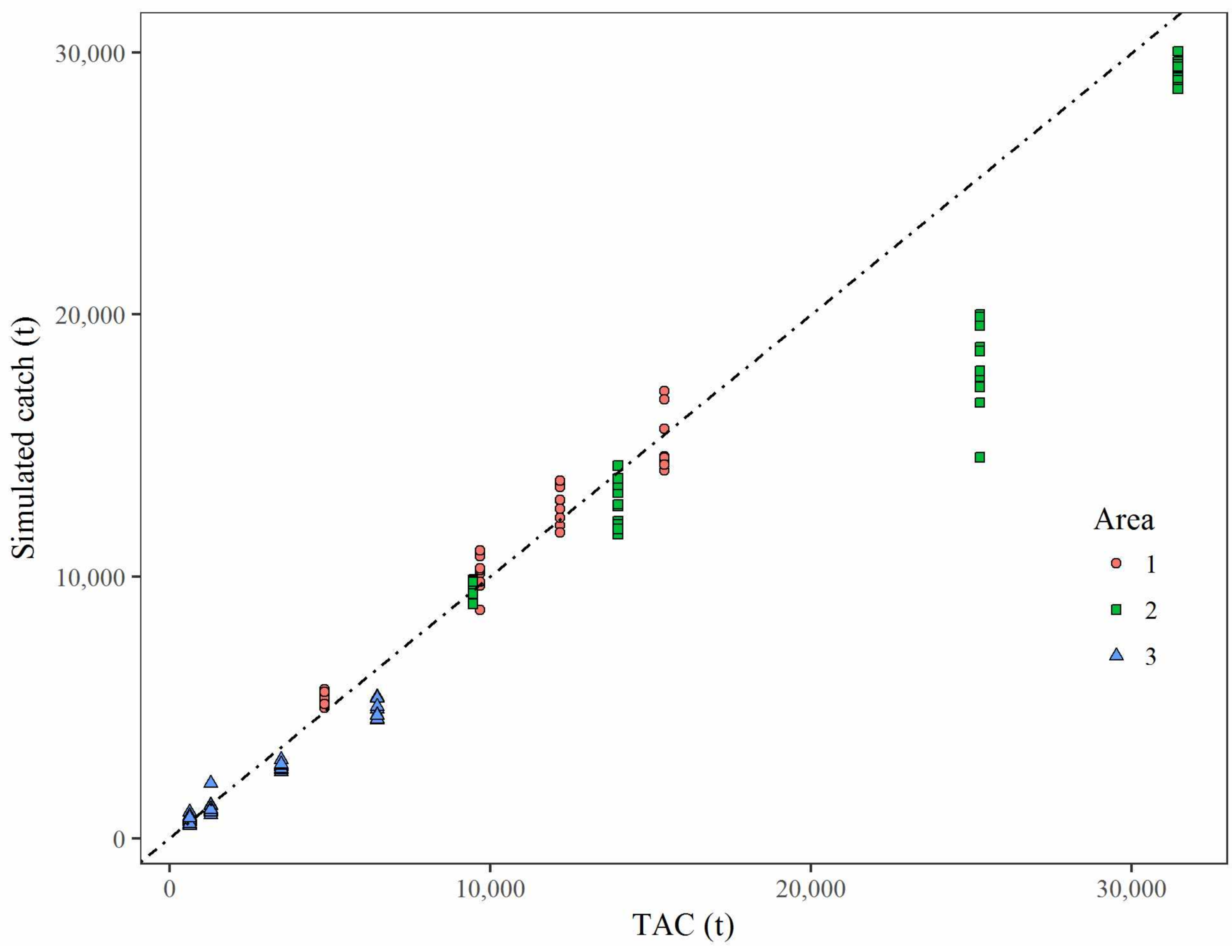

Figure 4.3. Comparison of allocated TAC to simulated catch by area, using 2014 TAC levels. The simulation was replicated ten times to account for stochasticity in the model structure. The closer a point is to the dashed 1:1 line the more accurate the simulated catch is relative to the allocated TAC.

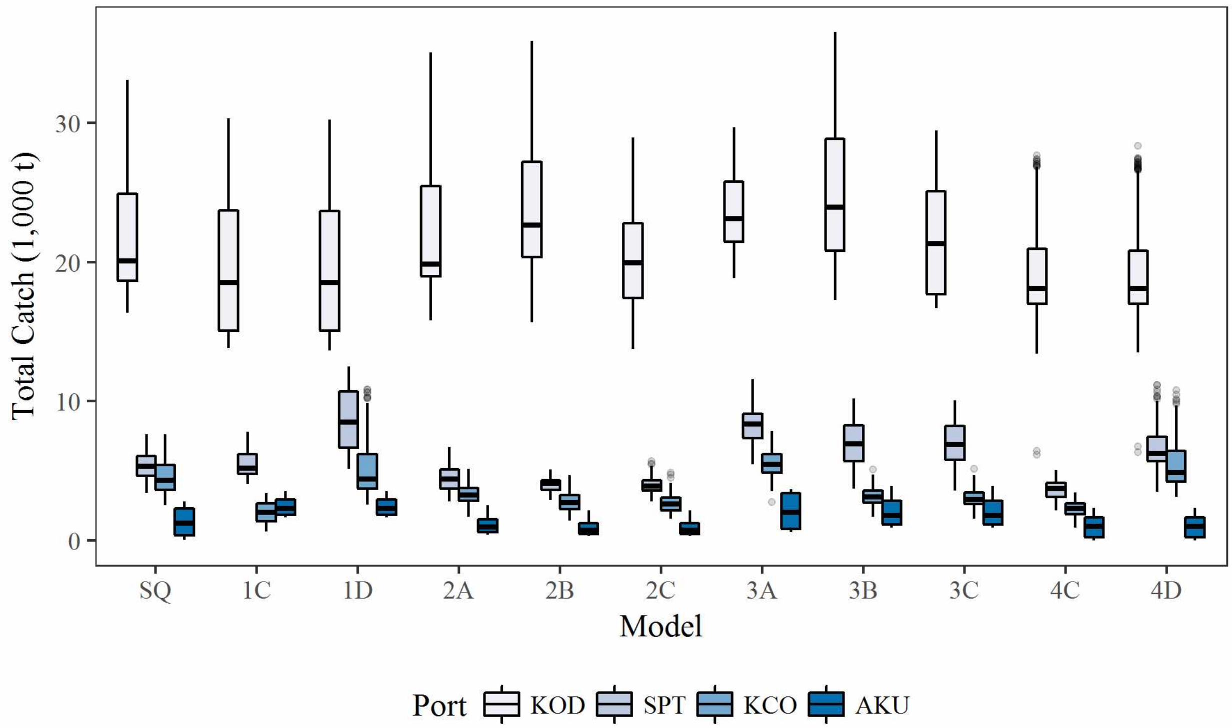

Figure 4.4. Total catch delivered to each port for 40 replicates of each management scenario.

Total catch is substantively different between ports and scenarios (Figure 4.4). There is a general trend whereby the majority of the catch is returned to port 1 (Kodiak), with ports 2-4 receiving reduced catch, respectively. Relative to the status quo, some scenarios have greater catches for all ports, e.g., scenario 1D and 3A, or reduced catches, e.g., scenario 4C. When the CV of catch is considered, some management scenarios have better properties than do others (Figure 4.5). The scenarios that allow for IFQ or cooperatives in federal waters tend to reduce catch variability. These are anticipated results as the IFQ and cooperative scenarios are intended to increase the efficiency of the fleets. Scenarios based upon catch-share community allocations or bycatch/PSC allocations tend to increase variability in catch or are similar to the variability observed in the status quo scenario.

Ex-vessel and fuel prices have substantial impacts on simulated revenue and the CV of simulated revenue across all management scenarios (Figure 4.6). The influence of ex-vessel price is most readily noted for port 1, i.e., Kodiak. There is a strong positive relationship between price per ton and net revenue. The inflection point for positive revenue for Kodiak (port 1) is ~$220/t at a fuel price of $0.80/l. There is a similar threshold for the other ports, though the change in net revenue is greatly reduced likely due to fleet characteristics. There are far more large-sized vessels with higher operating costs that home port in Kodiak than in other ports. These larger

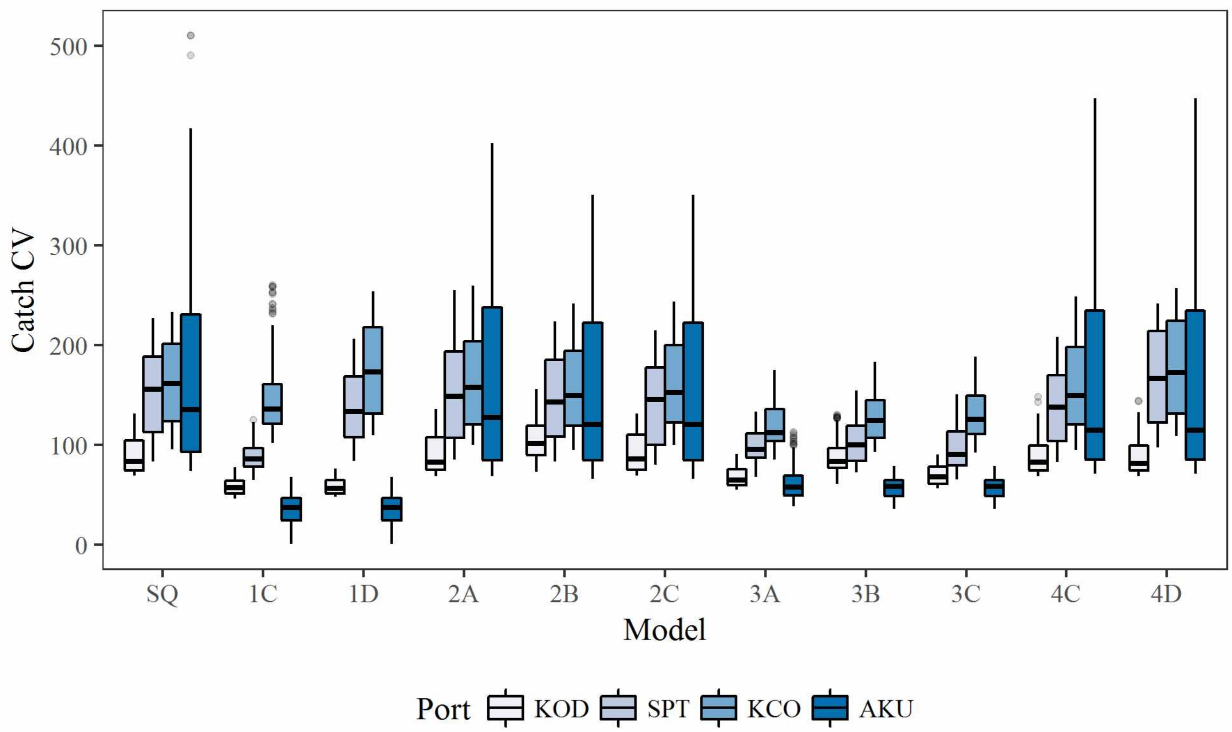

Figure 4.5. The CV of total catch delivered to each port for 40 replicates of each management scenario.

vessels have substantially higher operating costs than those assigned to the smaller vessels typically home-ported in Sand Point (port 2) and King Cove (port 3). Akutan (port 4) is the home port to few vessels that fish the GOA and therefore receives limited revenues from GOA pollock. If fuel costs are high and ex-vessel prices are low, the CVs of revenues are low (Figure 4.7), because each trip is of low value. The same CV behavior is observed when fuel costs are low, and ex-vessel prices are high because individual trips are of consistently high value. Some CVs have different trends between different state variables and ports due to the previously mentioned differing revenue inflection points for different fleets by port.

It is desirable to have increased revenues associated with increasing quota (see Figure 4.8 scenario 3A, King Cove [port 3]). However, revenues approach asymptotes for many of the ports, indicating a decline in marginal rent values (see Appendix D). As results presented in these figures are averaged over five simulations some of the asymptotes decline at higher levels of quota. The rate of change is also important; the steeper the curve is toward increased profits, the greater the marginal rent. It is of note that all of the ports show potential negative revenues at the lowest ex-vessel prices and highest fuel costs, with the port of Kodiak (port 1) having the strongest negative response.

Given the input characteristics of these simulations the management strategy that produces the best overall improvements relative to status quo is scenario 3A. In this scenario, federal waters are managed under an LLP with the ability to form cooperatives while state waters are managed in parallel as open access. This scenario produces generally higher net revenues for all ports (assuming ex-vessel and fuel costs are amenable; Figure 4.8), and has revenue CVs in line with status quo (Figure 4.7), but has catch CVs that are greatly reduced from status quo (Figure 4.5). One caveat of this management strategy is that it was not evaluated with an increase in participants; net revenues for a given port will vary depending upon size and number of vessels, as well as participation levels.

While strategy 3A may be the best option for the management target of revenue by port, it may not be the strategy that meets other management objectives. For instance, it is highly desirable that the pollock fleet in the GOA keep PSC to a minimum and Proposal 44-5 was initially brought forward to increase, or at least retain small vessel participation in the fishery. While these objectives have not been evaluated directly within this strategy, it is entirely possible to evaluate the PSC management strategy using the LLP with cooperatives framework in federal waters as the underlying management strategy or compare the potential for small vessel participation by port. There are numerous factors at play when evaluating a fishery such as the potential to enter other fisheries, seasonal exclusions, catch, and fleet behavior that managers need to consider that may not be addressed within a single framework. Additionally, there are base assumptions that can be

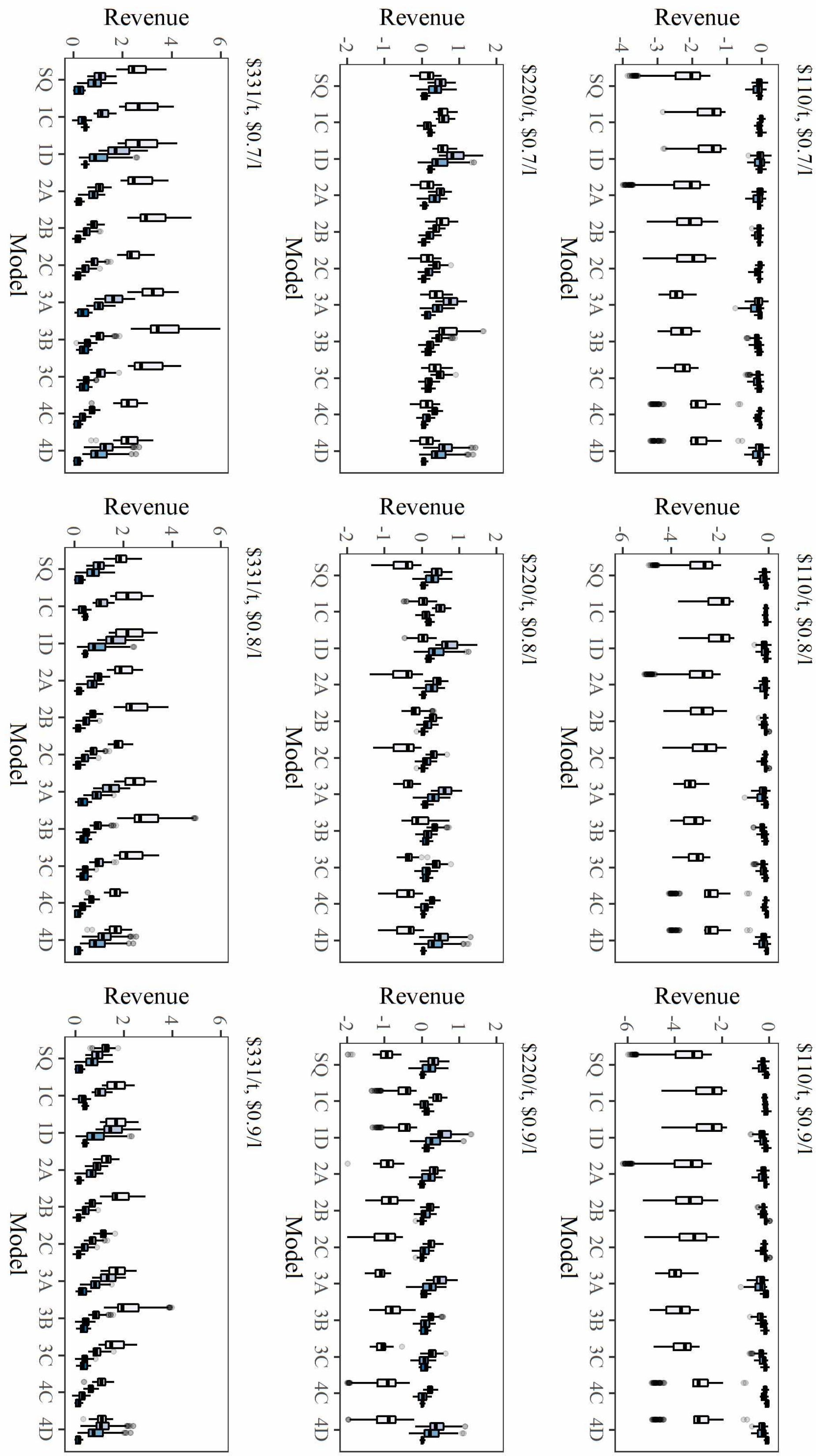

Figure 4.6. Simulated net revenue by port for 40 replicates of management scenarios. The ex-vessel value $/t and fuel costs $/l are listed at the top of each figure pane. Ports are arranged from port 1-4 from left to right for each scenario.

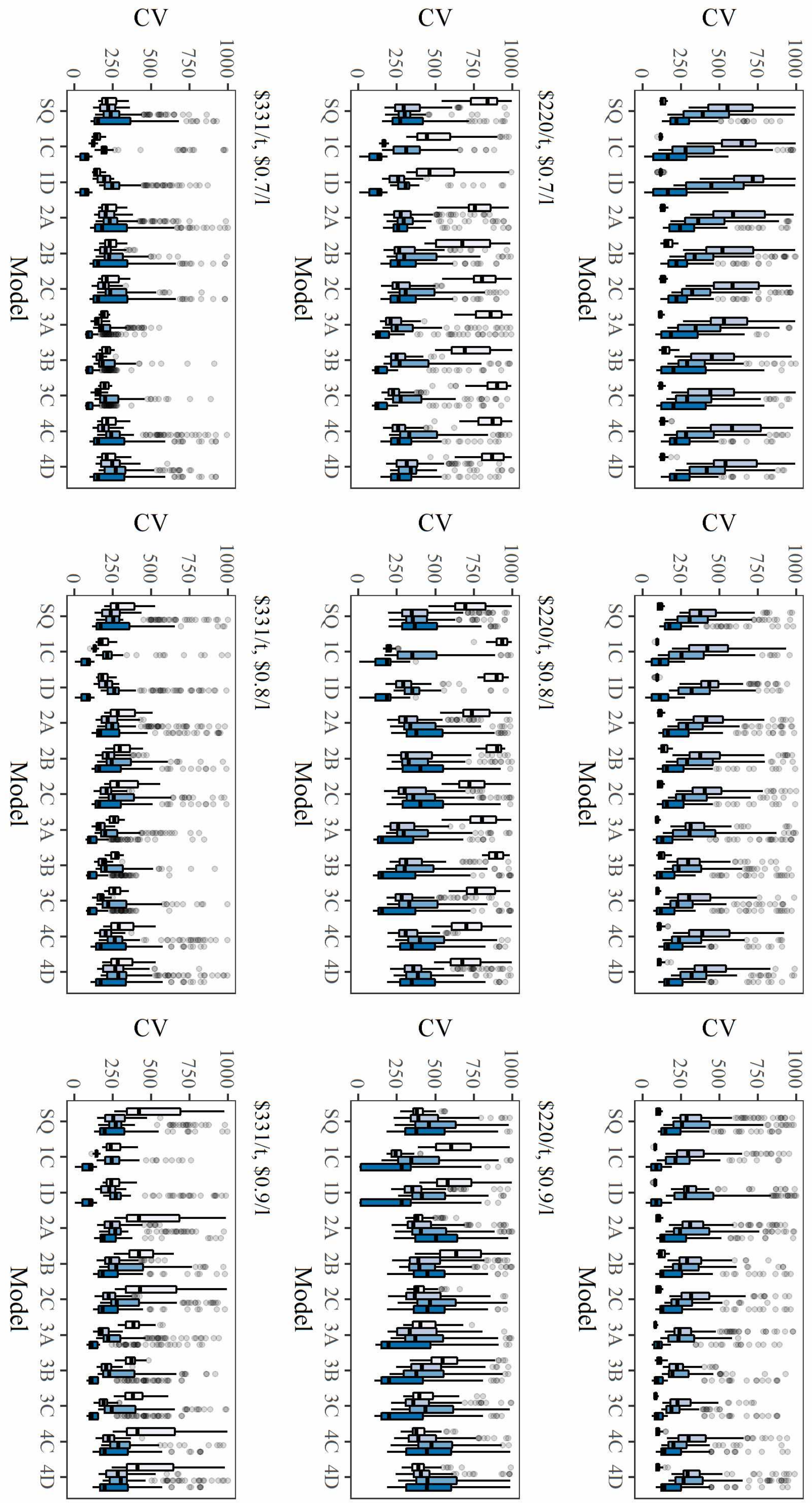

Figure 4.7. The CV of simulated net revenue by port for 40 replicates of management scenarios. The ex-vessel value \$/t and fuel costs \$/l are listed at the top of each figure pane. Ports are arranged from port 1-4 from left to right for each scenario.

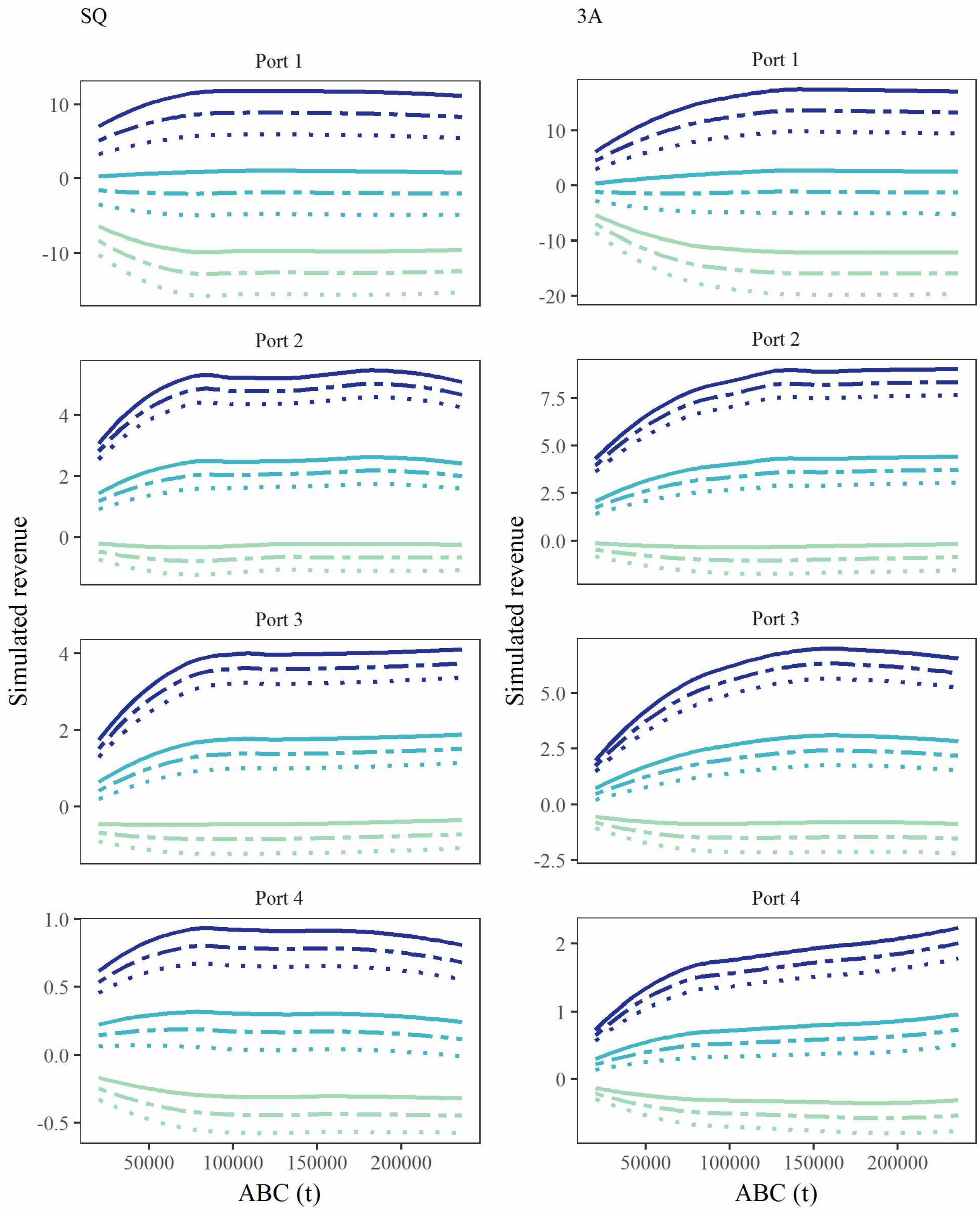

Figure 4.8. Net revenue by port from sequential ABCs. At the top of each figure pane, the number and letter designate the management scenario presented, SQ = status quo and 3A = LLP w/ability form cooperatives in federal waters and open access in state waters, see Table 1. The line types represent fuel costs: solid = \$ 0.70/l, dashed = \$0.80/l, and dotted = \$0.90/l. The line colors indicate ex-vessel value: light green = \$110/t, aqua marine = \$220/t, and dark blue = \$331/t. Note that the scale of the y-axis varies.

evaluated, e.g., all catch allocated to a state waters by area and season is available to be caught. Spatial examinations of historical catch trends may show that such an assumption is invalid.

This ABM has been built in a compartmentalized manner for flexibility to facilitate future incorporation into other biological or economic models. For instance, if further examinations of IFQ type scenarios were desired, this model could be coupled with a dynamic catch-share trading model, such as the IFQ trading scenario presented in Little et al. (2009). This ABM could also be incorporated into or draw from the results of management strategy evaluations to examine potential biological and economic impacts from changes in the environment or management strategies. Last, it may be possible to couple this type of model with discrete individual events, such as those presented in Watson and Haynie (2016), as a method to more accurately account for costs (travel time).

4.5 Conclusions

The primary purpose of this exercise was to develop an ABM with a framework that can be utilized to examine alternate management strategies of fishery resources. This objective has been met with the development of a modular framework that is readily adaptable to alternative management scenarios, can be utilized in conjunction of other models of stock allocation or vessel interactions, and has been developed in a widely utilized coding language, that can be adapted in a reasonable time frame for addressing management concerns for other fisheries in Alaska, or the world.

While the stylized fishery presented in this paper is grounded in recent fisher behavior for the pollock fishery in the Gulf of Alaska, it is not necessary to have such a highly developed input structure to address management questions such as those presented throughout this paper. Such an ABM could easily be adapted for data-limited management scenarios, utilizing different métiers and informing input parameters with expert opinion. Coupled with sensitivity analyses such examinations could produce dynamic model outputs, thus providing managers another tool to help guide decision making.

We do not propose the use of this (or any) type of model as the sole deciding factor about how to establish new management structures. There are social, political, and ecological aspects that may not be adequately addressed by such simulations. Nevertheless, we suggest that there is a role for ABMs, such as the one presented here, as managers continue to work toward implementing ecosystem-based fishery management.

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Chapter 5
General Conclusion

The multiple analyses and simulations presented are one small effort toward being able to consider the Gulf of Alaska walleye pollock population within an ecosystem context. While examinations of reproduction biology and management scenarios for walleye pollock in the Gulf of Alaska do not address every question, these incremental additions to our collective knowledge of the species could lead to improvements in our ability to manage the species in a more holistic fashion.

Once spatial patterns in maturity were accounted for (Chapter 2), a clearer picture of walleye pollock maturity estimates emerged, showing less annual variability by length or age and likely providing more reasonable estimates, given our understanding of fish populations. This correction led to an understanding that the methods currently used for determining harvest levels are conservative in nature. This spatial correction also allows for further examinations of walleye pollock maturity relationships with body condition, and with environmental and population factors (Chapter 3). Similarly, fecundity analysis of archived ovary samples provided contemporary estimates of fecundity that were also examined within the context of body condition, and environmental and population effects. Fecundity and maturity have similar relationships, in that they appear to be density-dependent, and generally be positively affected by ocean temperature. Summertime chlorophyll-*a* concentrations were found to show dissimilar effects on maturity and fecundity. A dome-shaped response is observed for maturity; possibly this is due to a poor prey base at both low and high concentrations. Low chlorophyll-*a* concentrations do not support a strong prey base and high chlorophyll-*a* concentrations means that the prey population of pollock is low. The relationship between fecundity and chlorophyll-*a* is strongly negative as concentrations increase. When comparing a measure of reproductive potential based upon total egg production to the spawning stock biomass estimate used in the current stock assessment it becomes apparent that there is a bias between the estimates. This effect presents itself most readily at age-4 and age-5. This effect leads to periods in which the harvest rates are consistently higher or lower than intended by the harvest control rule. Therefore, monitoring the stock demographics as well as regularly updating indices of fecundity is encouraged.

The question of how best to coordinate resource management activities is a long-standing issue. There may be options that address social, political, and legal needs while providing reasonable economic gains and management of the resource for long-term sustainability. Agent-based models, such as the one presented in this study (Chapter 4), provide a valuable method for quantitatively defining what is often inferred intuitively. By quantifying methods, the assumptions are clearly stated and examined in full which should help guide the decision-making process. The model presented herein is a framework that can be used for quantifying the effects of alternative management strategies, in detail, prior to implementation. This, this modeling approach provides a useful tool for policymakers.

The results found in this study, both in terms of biological/ecological relationships and socio-economic characteristics, can help inform current management strategies. The maturity models presented herein can be directly incorporated into the stock assessment, and the fecundity information can be utilized to determine a stock recovery time. The agent-based model can be implemented to provide policymakers with another decision-making tool, though this model would likely need to be tuned to specific management questions. Nevertheless, the framework is in place and can be adapted to other questions with relative ease.

A potential future research avenue would be to establish a management strategy evaluation (MSE) examining whether the current or alternative management strategies are robust to variability and uncertainty in the reproductive biology of the walleye pollock stock. Including reproductive biology (growth, fecundity, maturity) and including observed relationships with environmental variability and population size within an MSE will allow for an examination of the consequences of these variables on harvest strategies. Further, this method of examining population dynamics lends itself to the ecosystem-based fishery management framework in that it provides an ability to examine what has occurred and allows for predictive capabilities to changes in environmental or management scenarios.

Last, policymakers likely have a short list of management scenarios for the walleye pollock fishery that they would prefer. This list could be addressed in greater detail with an agent-based model to provide substantial insight into the underlying dynamics of the fishery and management influence before making substantive changes that may have unintended impacts on the economic viability of the fishery. Additionally, this model could be "piggybacked" onto an MSE to provide a dynamic biological/economic model.

Appendix A

Fecundity

Question:

Are the field weight and lab weights similar enough to be used as a mean values for fecundity estimation?

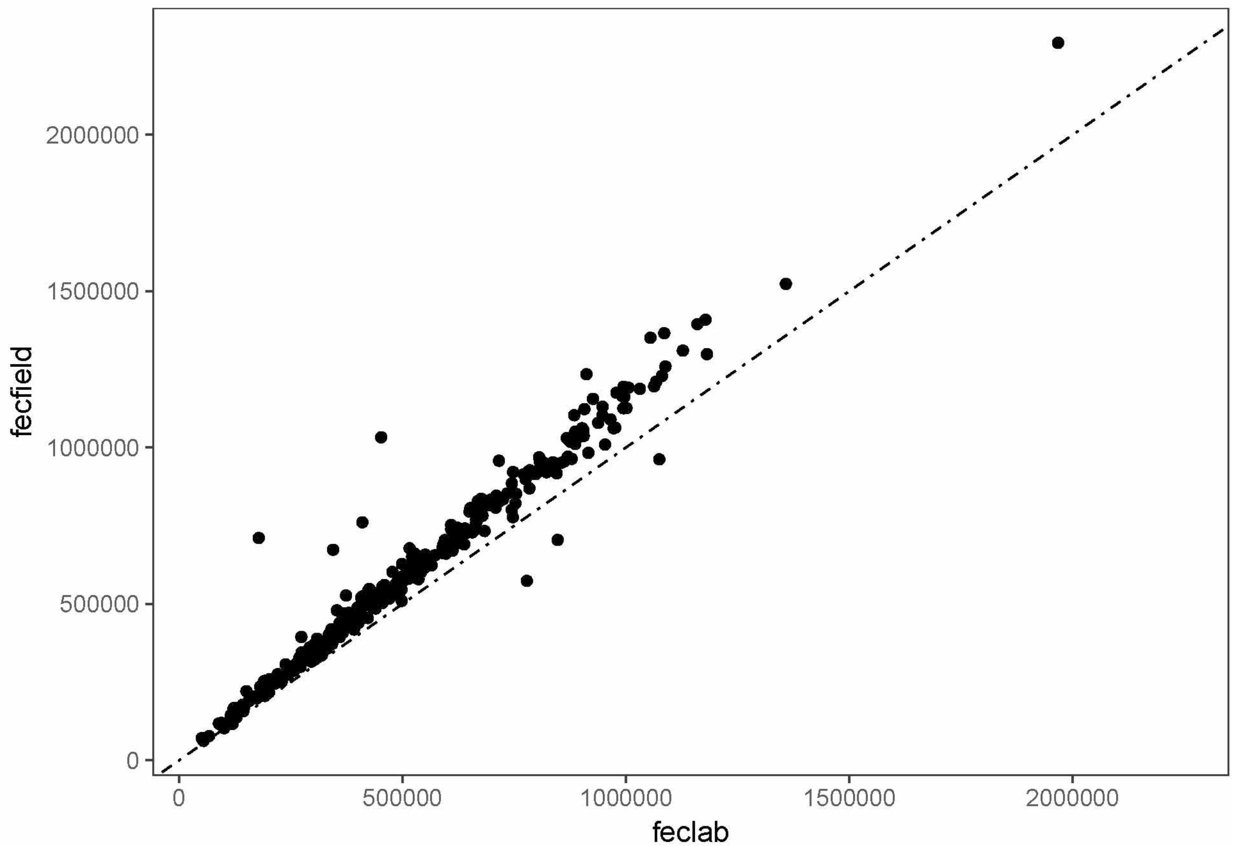

Figure A.1. Estimates of fecundity based upon field weights or lab weights. There appears to be some bias.

This is necessary as some samples only have one or the other measures, though most have both.

$$lm1 = lm(\mathit{field\ wt\ fecundity} = \mathit{laboratory\ wt\ fecundity}) \tag{A.1}$$

$$lm2 = lm(\mathit{laboratory\ wt\ fecundity} = \mathit{field\ wt\ fecundity}) \tag{A.2}$$

Correct for the bias via linear model. Use the field weight to determine fecundity as it is likely less biased due to formalin storage.

A:

The two measures of fecundity are similar enough to be averaged for the analyses in this dissertation.

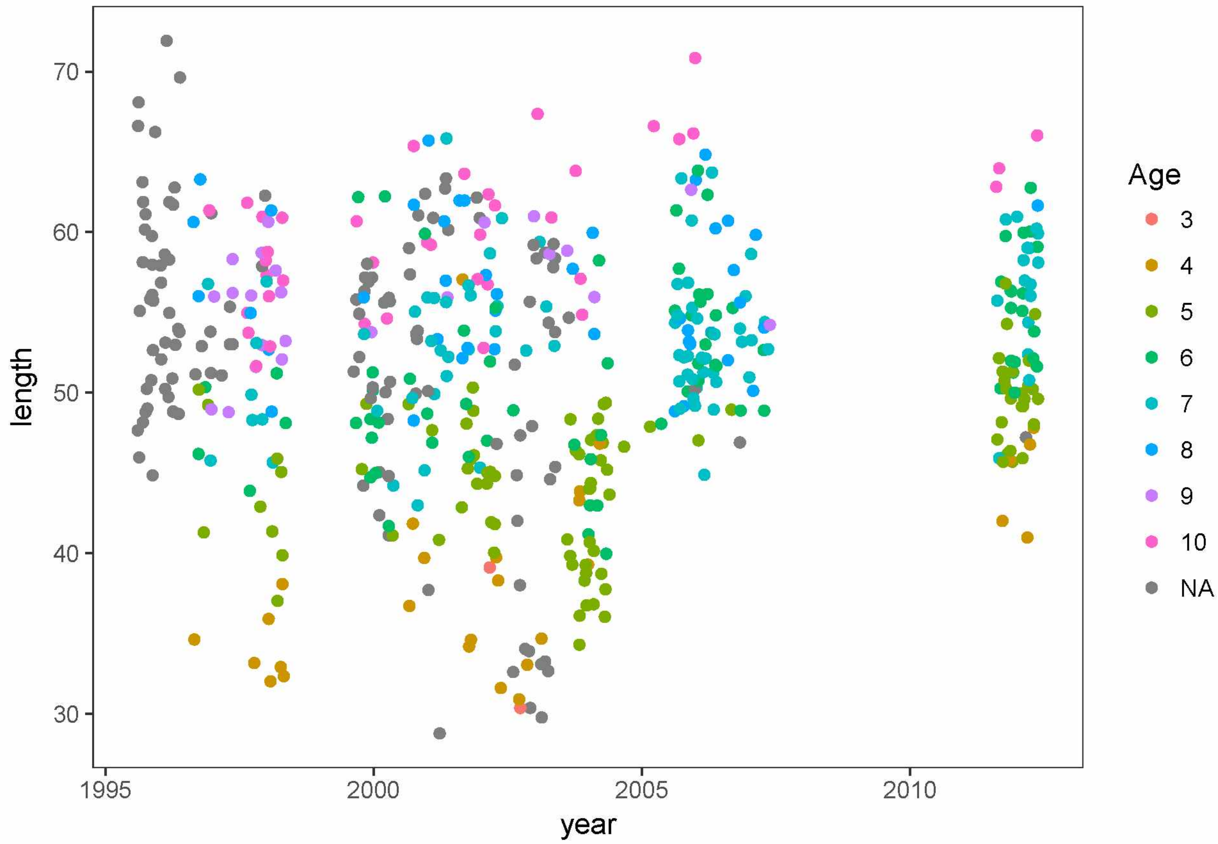

Figure A.2. Length of pollock collected for fecundity analysis, by age and year.

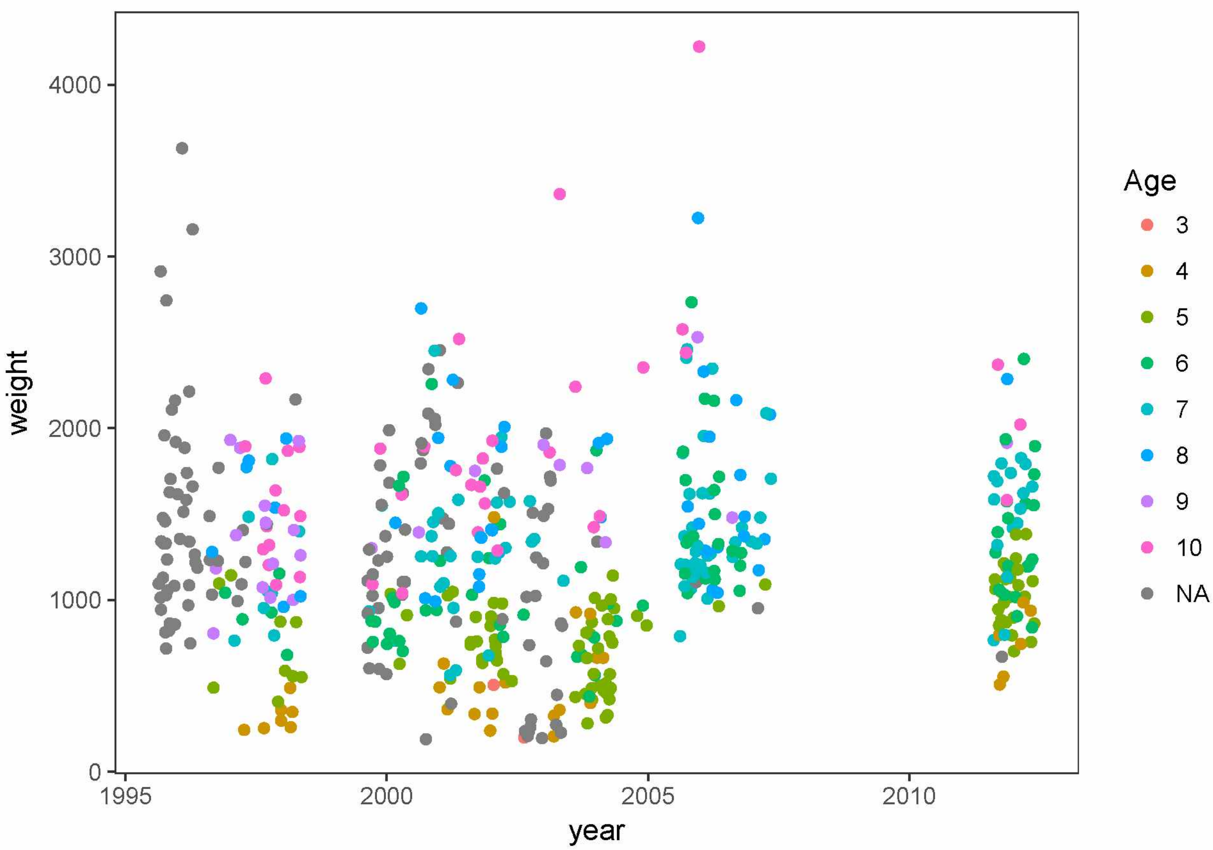

Figure A.3. Weight of pollock collected for fecundity analysis, by age and year.

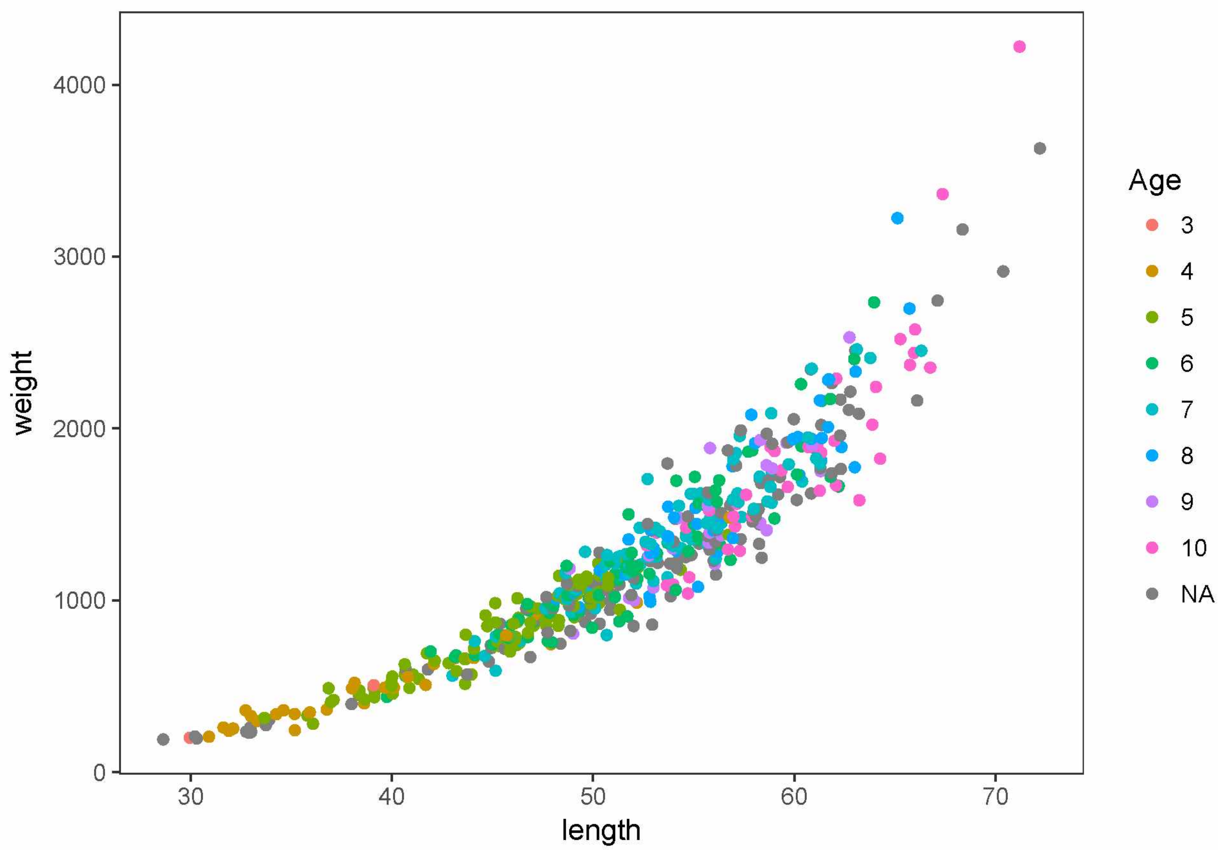

Figure A.4. Length-weight relationship of pollock collected for fecundity analysis, by age.

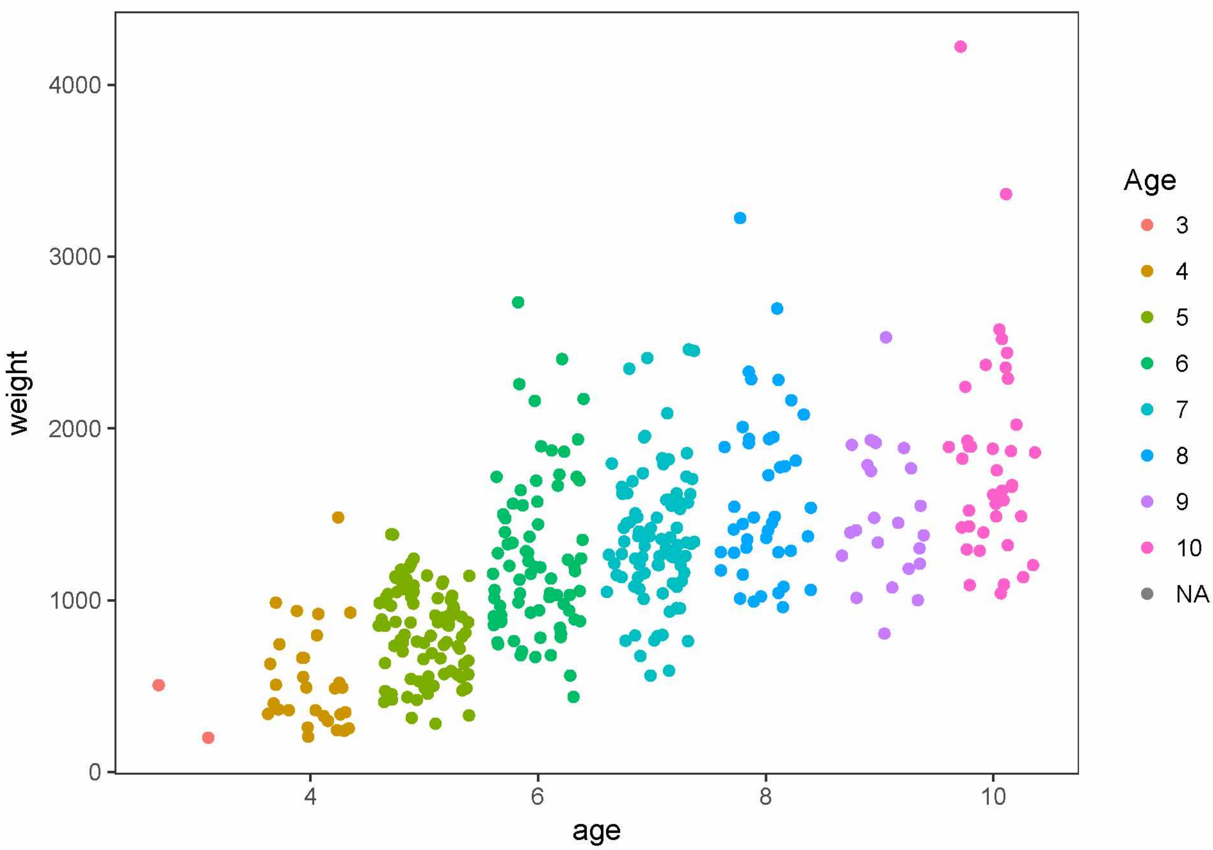

Figure A.5. Pollock age-weight relationship for samples collected for fecundity analysis.

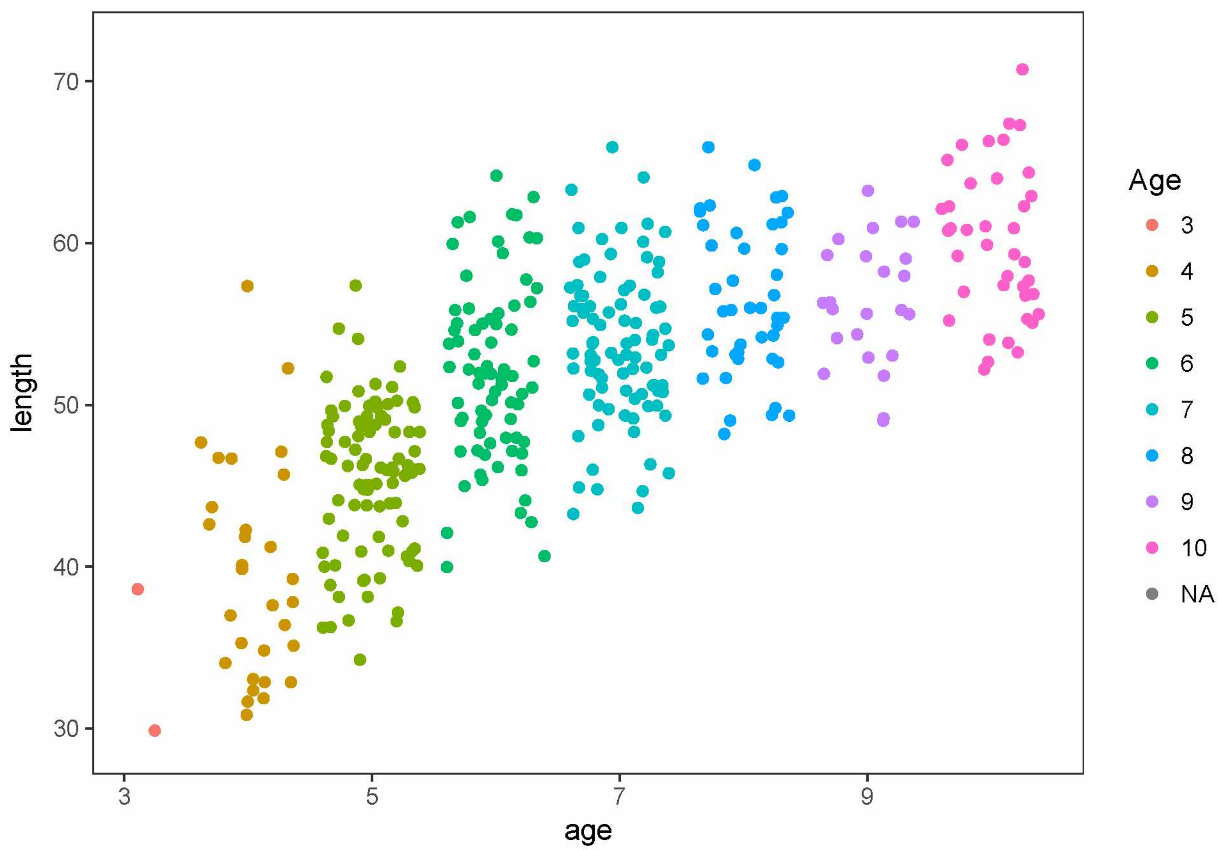

Figure A.6. Pollock age-length relationship for samples collected for fecundity analysis.

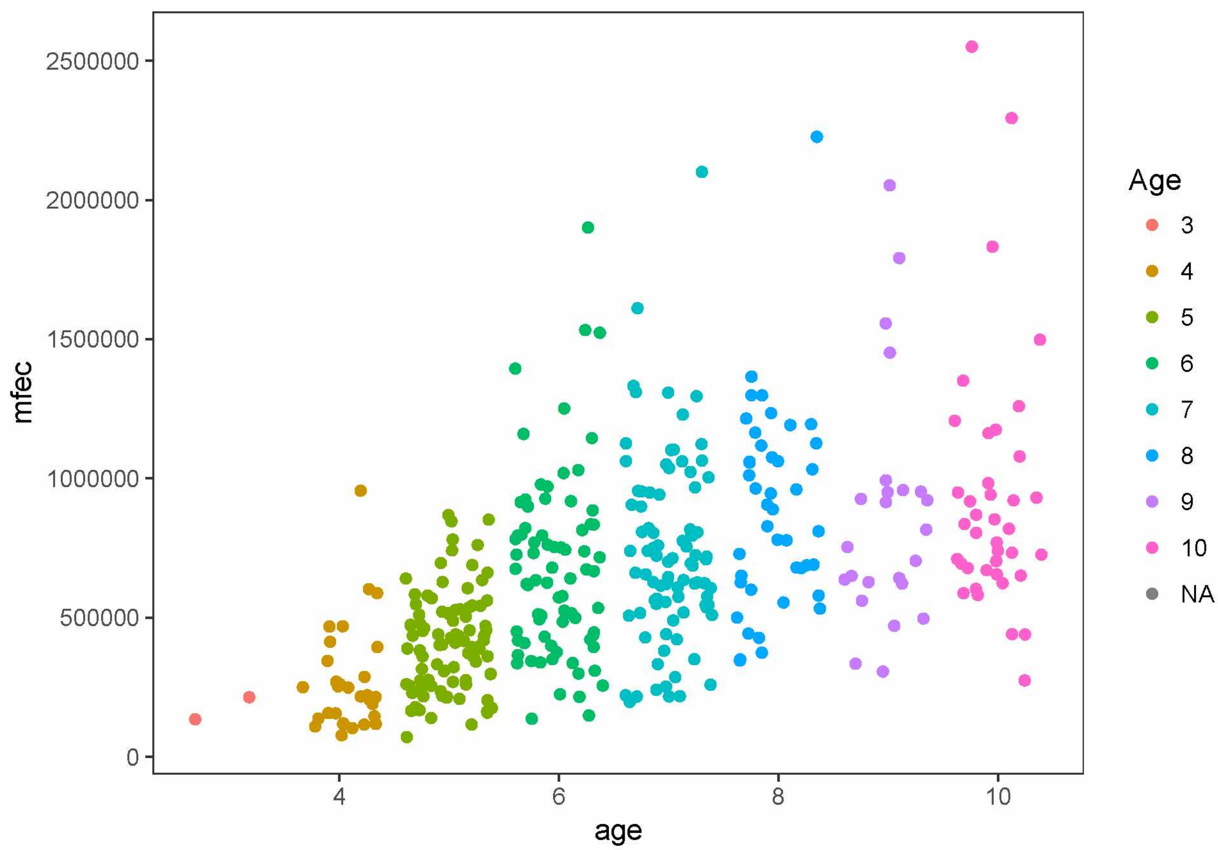

Figure A.7. Relationship between pollock age and potential fecundity.

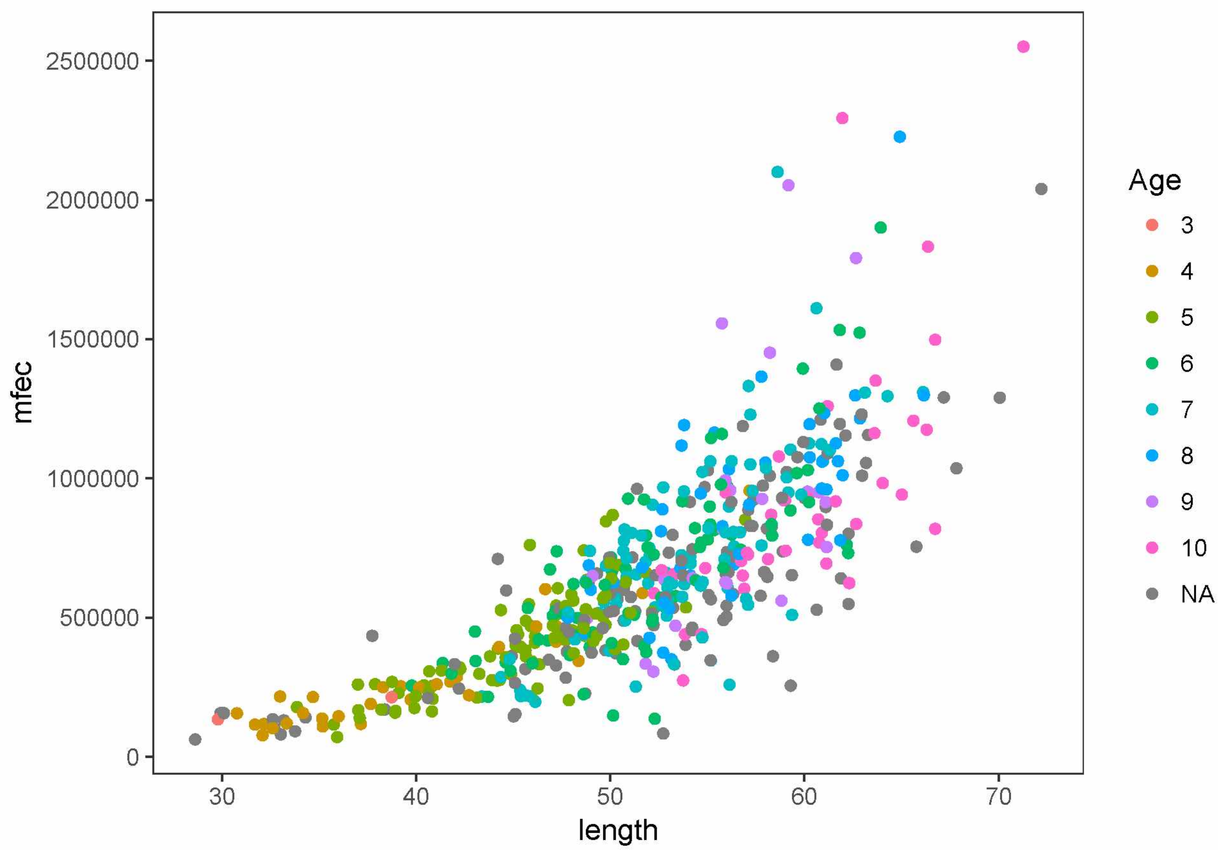

Figure A.8. Relationship between pollock length and potential fecundity.

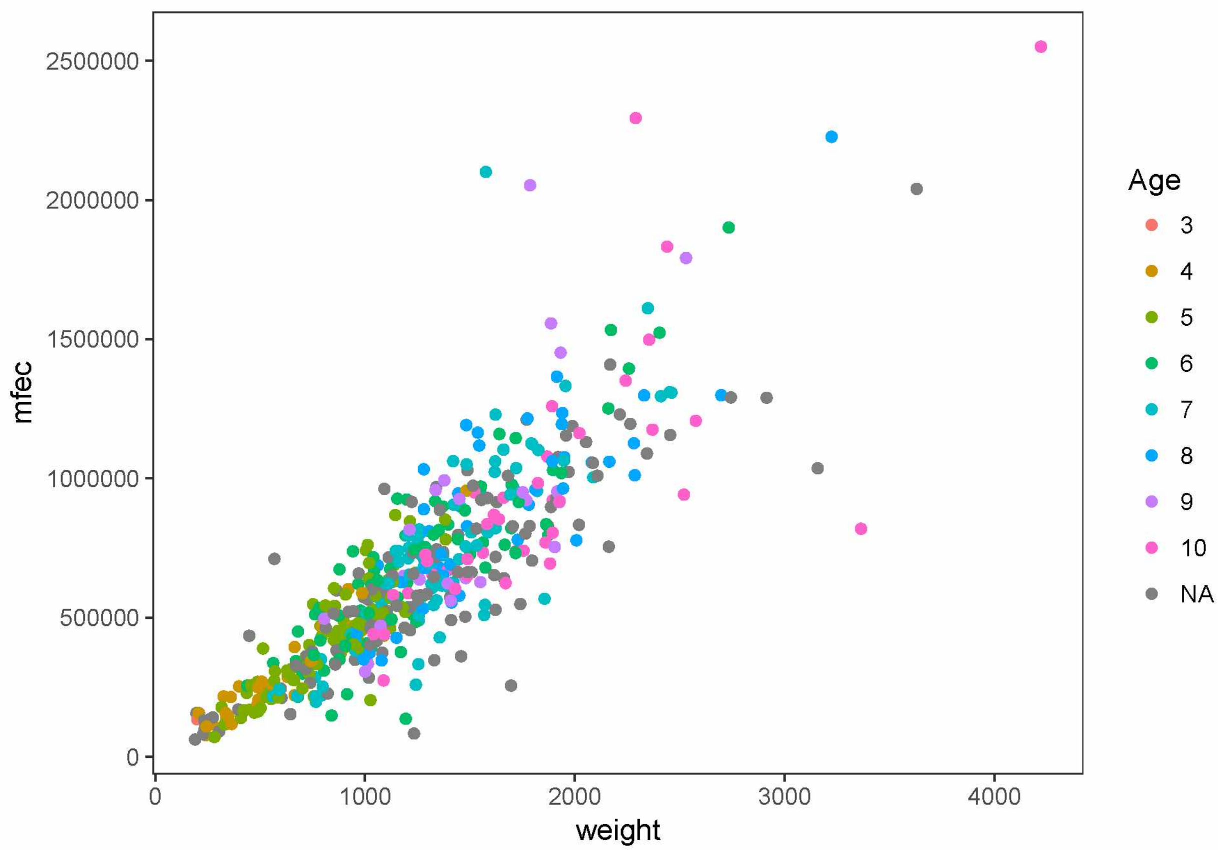

Figure A.9. Relationship between pollock weight and potential fecundity.

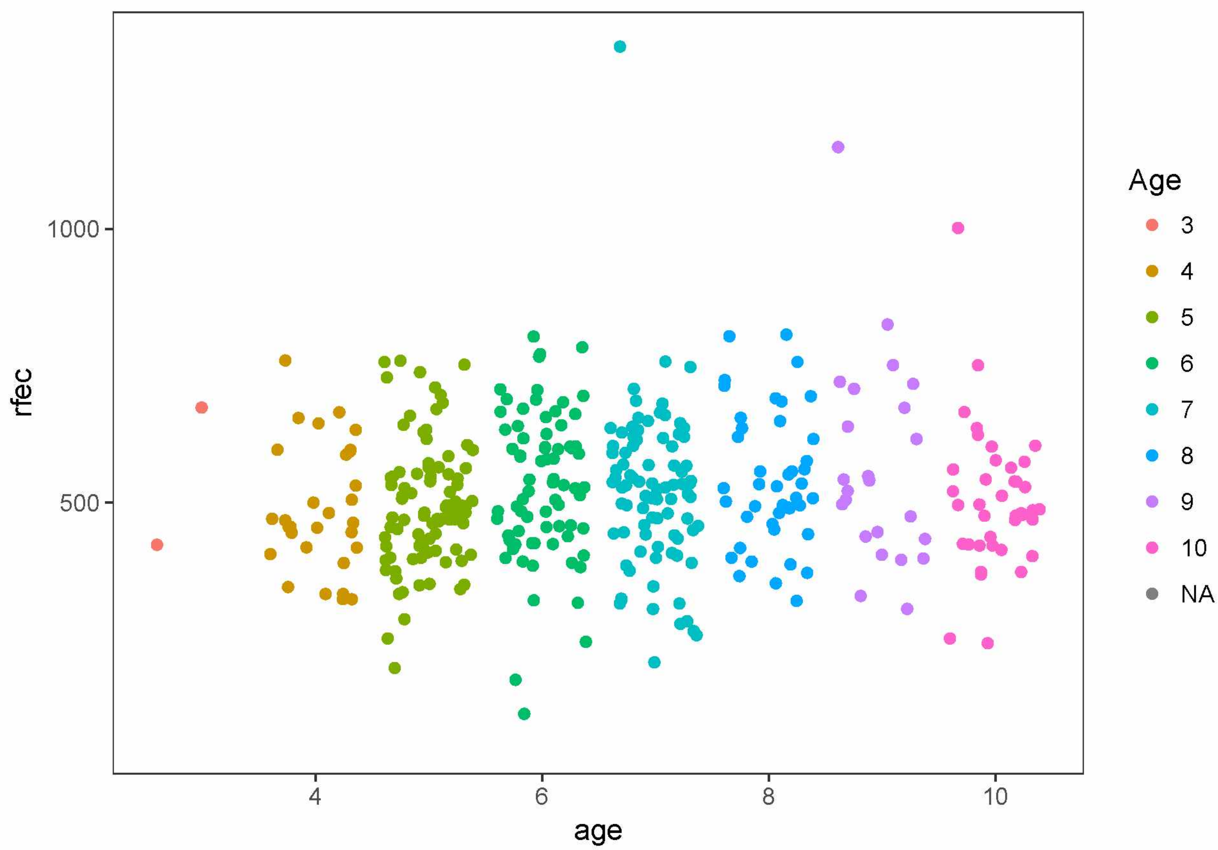

Figure A.10. Relationship between pollock age and relative fecundity.

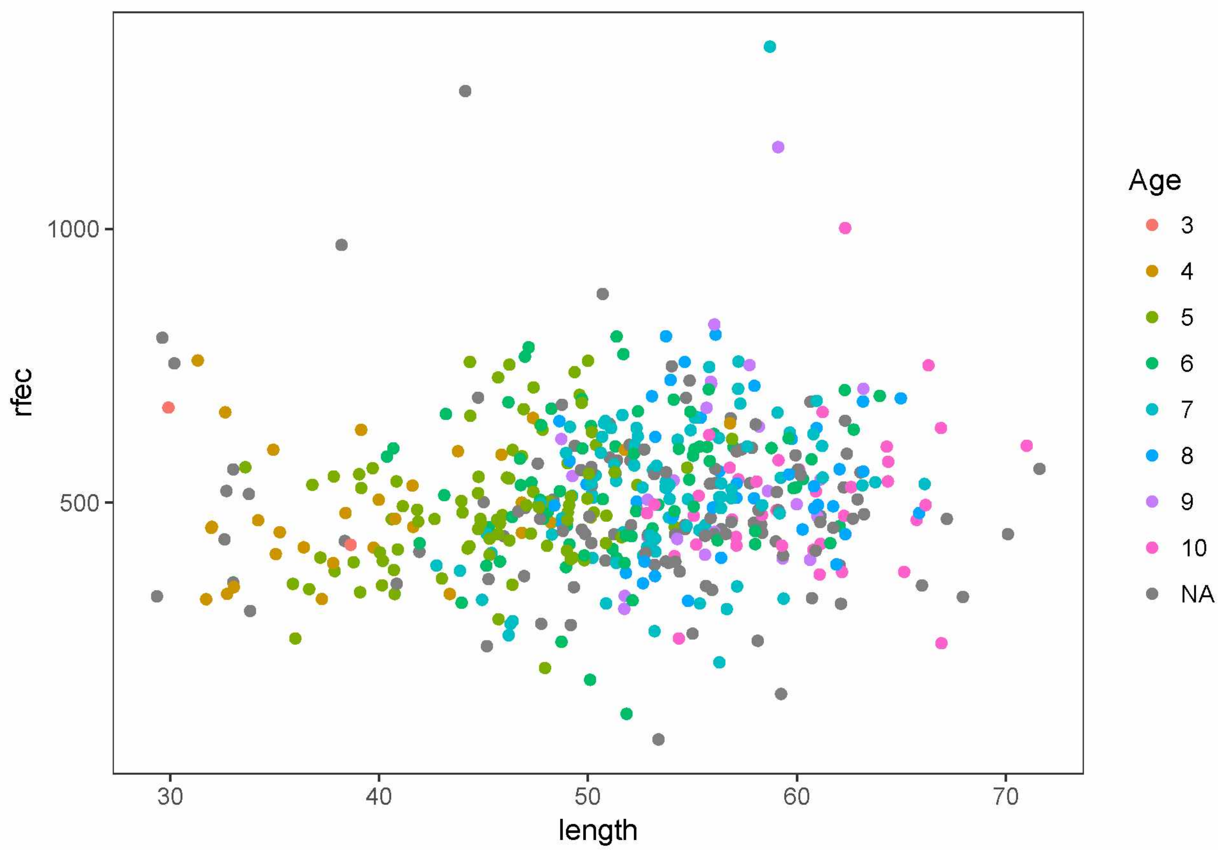

Figure A.11. Relationship between pollock length and relative fecundity.

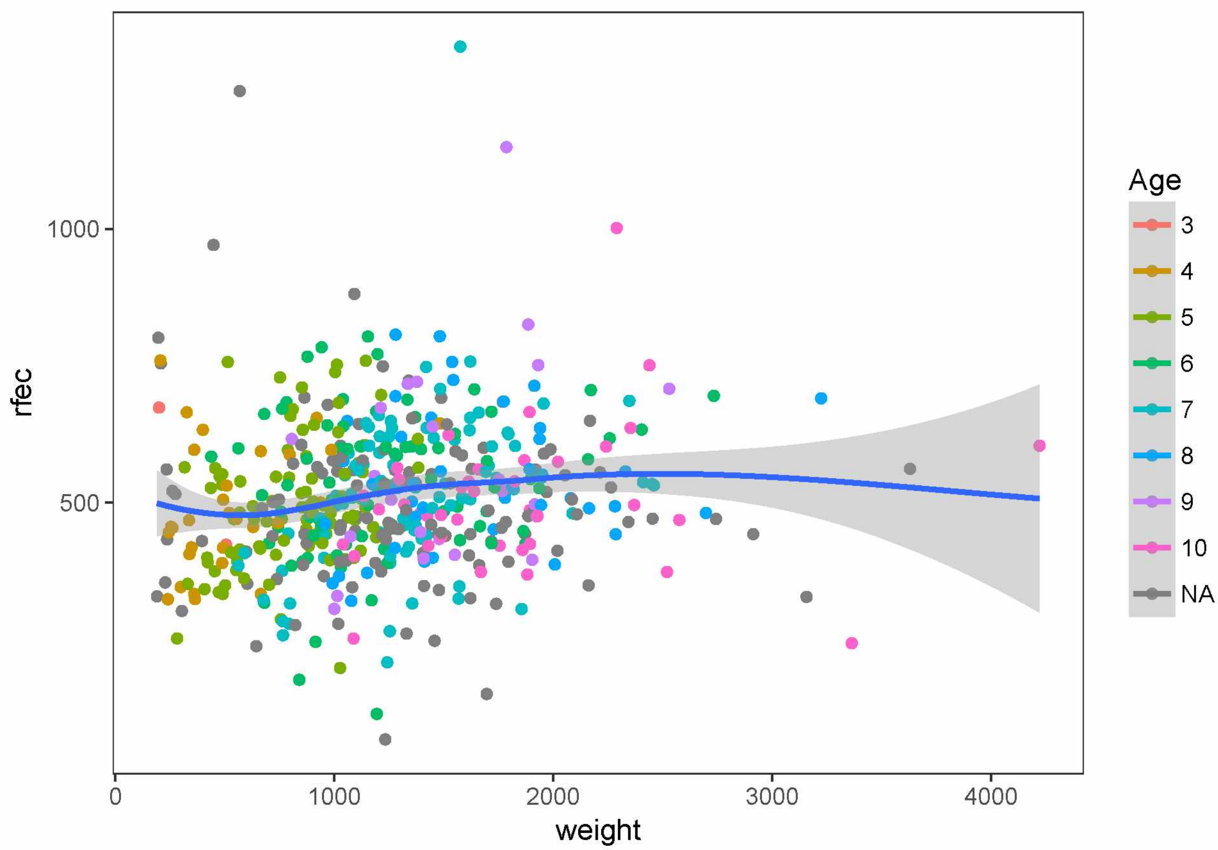

Figure A.12. Relationship between pollock weight and relative fecundity.

Appendix B

Scenarios

Basic descriptions of model structures and associated code to produce model output.

All code is available at:

https://github.com/ben-williams/parallel_diverge

Code modules There are a number of .R files necessary to run these models

- 'helper.R' - this file holds the R libraries to be loaded, links to data sources, and provides a few general model check/helper functions.
- 'gridsearch.R' - these functions add a penalty by port and fishing location to travel times, the assumed catch (t) and assumed number of days for a trip are set in this file.
- 'search_patterns.R' - provides the functions that are gridsearch optimized, they call the 'f.grid' function from the gridsearch.R file.
- 'tac.R' - provides vessel behavior, number of vessels, tac allocations (area, port, vessel, fishery), sets the ABC input levels, and provides functins for splitting the TAC into appropriate list structures for simulation.
- 'simulation.R' - provides the simulation functions for all the variable management scenarios.
- 'cleanup.R' - provides a revenue calculation function
- 'model.R' - sources all the above R scripts for ease of implementation.

The general mechanics of the model structure are as follows:

- 4 seasons
- Catch (year, season, area) as reported by NOAA https://alaskafisheries.noaa.gov/fisheries-catch-landings
- 4 vessel size classes (¡60, 60-90, 90-125, 125+) with separate horsepower ratings (500, 750, 1,000, 1,500) to account for fuel usage the number of vessels were set for each port, and season
- 4 ports (Kodiak, Sand Point, King Cove, Akutan)
- 3 fishing areas (610, 620, 630)
- catches modeled on truncated normal or log normal distribution draws by size-class

- trip duration based upon normal distribution draws for each vessel by port, and season
- the probability of a vessel fishing was estimated for each vessel by port and season based upon $trips * day/tday$, where *trips* is the total number of trips, *days* is the average trip duration, and *tday* is the season length

Status Quo Scenario This scenario calls the 'tac.baseline' function that apportions the ABC to each area and season. This functinos calls the 'f.boats' and 'f.trip_behavior' functions to provide vessel characteristics that are aligned with the current parallel fisheries in federal and state waters.

The 'f.simulation' function is then called that runs the simulation. There are constraints such that the catch in areas 1 and 2 do not exceed 90% of the TAC and area 3 does not exceed 70% of the TAC. These constraints effectively act as a manager as all vessels fish concurrently and can easily overshoot the target TAC.

State Waters Scenarios

LLP - small vessels

This scenario calls the 'tac.state' function and uses state waters allocated ABC. This function provide the small vessel behavior 'f.boats_small'. The simulation function used in the status quo scenario is used here as well.

LLP - equal catch shares

This scenario calls the 'tac.state.ecs' function and uses state waters allocated ABC. This function provide the small vessel behavior 'f.boats_small' then splits the state waters TAC into equal portions for each participant by season, output is then split into individual lists for simulation. The simulation for equal catch shares 'f.simulation.ecs' is updated to include individual catch, as well as area catches (vessels have a catch-share quota, but can fish in any area). Controls are placed on TAC levels to reduce overfishing.

LLP - super exclusive

This scenario calls the 'tac.state.sx' function to provide small vessels by port and area. These vessels are then assigned an area they are permitted to fish, based upon historic use by season. The simulation function is similar to the status quo scenario though vessels are restricted in the areas where they can fish.

Federal Waters Scenarios

IFQ

The IFQ scenarios had individual TACs set via the 'tac.fed.ifq' function. This allocates TAC only to larger size-class vessels. If the maximum amount of pollock that a vessel caught by area and season and delivered to a given port was ¡100 t the vessel was not allocated IFQ. If the vessel had delivered ¿=100 t to a port from a particular area in a season the vessel was allocated a percent of the total as it relates to their previous catch (e.g., relative catch rates were maintained). The 'f.simulation.ifq' was established with controls to reduce overfishing of the TAC, though worked in much the same manner as the base 'f.simulation' model.

Catch-share community quota allocation

Parallel state waters This scenario calls the 'tac.port.all' function which allocates the tac to each port based upon historic average catch returned to each port via the 'f.port_allocation' function. The standard 'f.boats' and 'f.trip_behavior' functions are used to assign the number of vessels by port and vessel fishing behavior. The 'f.simulation.cq' function operates similarly to the 'f.simulation' function, though reduces the available TAC in area 3 to reduce overfishing.

Federal waters only This scenario works in the same manner as the parallel state-waters catch-share fishery, though the ABC reflects only the federal-waters ABC and only large vessels participate in the fishery.

LLP with ability to form cooperatives

Parallel state waters This scenario calls the 'f.tac.outcoop.all' and 'f.tac.incoop.all' functions to designate the vessels that are in the cooperative and out of the cooperative. Vessels in the cooperative are then filtered to remove those with lower efficiency. 85% of the permit holders are randomly selected to be in the cooperative, 15% of the vessels are not in the cooperative. Of the vessels in the cooperative, the last 5 years of the status quo model output were used to calculate the lower 5% quantile of vessel marginal profits. This lower 5% was removed from the fishery. Trip behavior was set as per the status quo method. The simulation function 'f.simulation.coop' was modified to provide a reduced TAC target, to prevent overfishing.

Federal waters only This scenario works in the same manner as the parallel state-waters cooperative fishery, though the ABC reflects only the federal-waters ABC and only large vessels participate in the fishery.

Bycatch/prohibited species catch allocations

The bycatch/prohibited species catch scenarios allocate TAC via the 'tac.fed.psc' function in the same fashion as the status quo method though the vessels are restricted to the larger size-classes, the federal ABC is used and a salmon catch rate by area and total salmon harvest values are included. The 'f.simulation.psc' function includes a salmon catch target, similar to the TAC targets by area.

Appendix C
Model Performance

Examination of whether the agent-based simulation model produces reasonable real world results.

Note: The raw CFEC data presented herein is confidential and therefore will only be presented in aggregate - if access to the data is desired please see: https://www.cfec.state.ak.us/forms/cdreqf.pdf

The data names and formats are as follows:

Table C.1. Data formats.

Variable	Data type	Notes
year	integer	
ton	integer	gross catch reported
port	integer	delivery port
area	integer	federal harvest area
p_holder	integer	permit holder
p_fshy	integer	permit type / vessel size-class
startdt	date/time	trip start date
landdat	data/time	trip end date
season	integer	fishing season

Four R libraries are needed for this evaluation. The data "pol.csv" are from the CFEC gross earning database, filtered to only include hauls where pollock were captured under statewide otter trawl permits (see https://www.cfec.state.ak.us/misc/FshyDesC.htm).

- here
- tidyverse
- truncnorm
- EnvStats

Anticipated catch was determined by vessel size-class. Vessel offloads less than 3,000 lbs were excluded from the input data, to remove bycatch offloads as opposed to targeted fishing. The simulation models assume a target catch of 50 t for each trip.

Anticipated trip duration was based upon the average trip duration by vessel size-class, for the simulations each vessel anticipated a trip of 2.5 days duration.

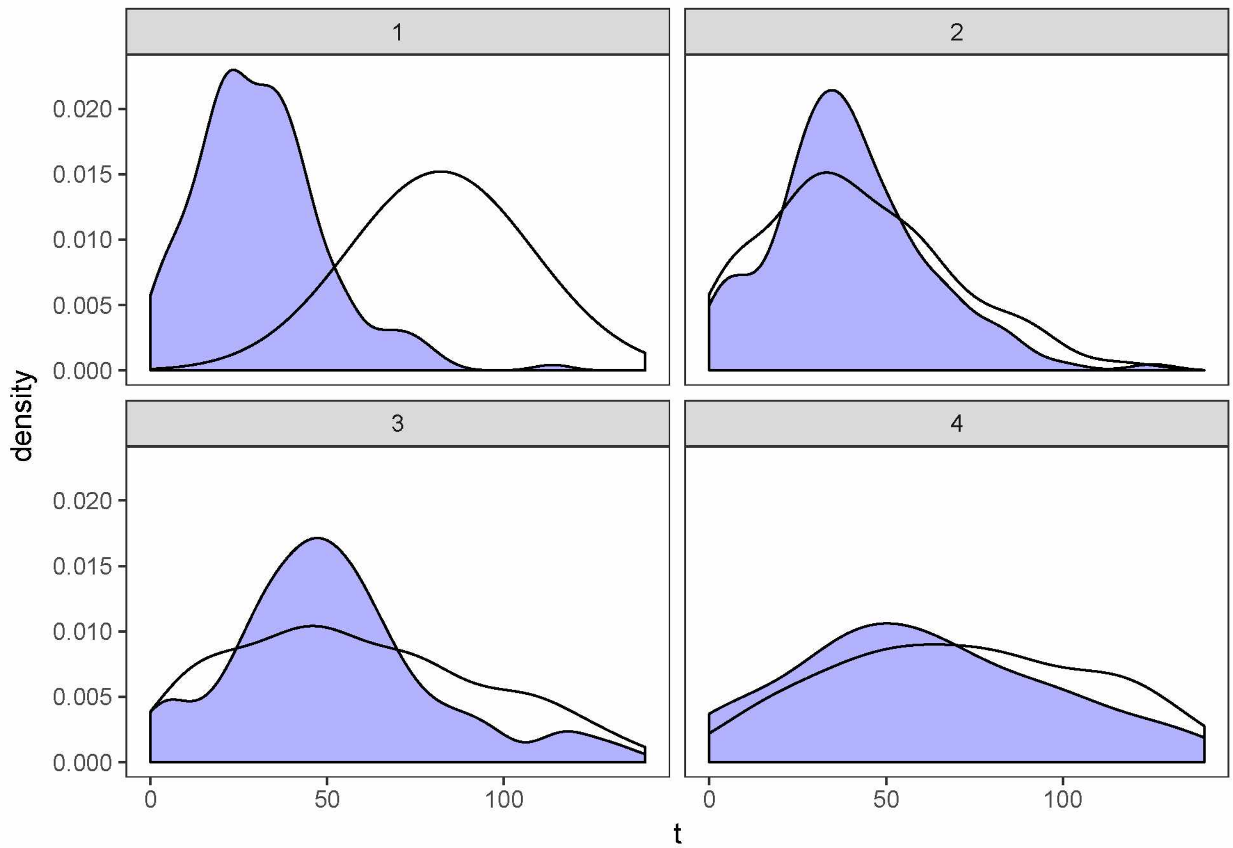

Figure C.1. Catch (t) by vessel size-class for all years combined. A lognormal distribution was used for vessels of size-class 1, all other vessels were based upon a truncated normal distribution. The shaded area is observed data, the black line is the simulated distribution.

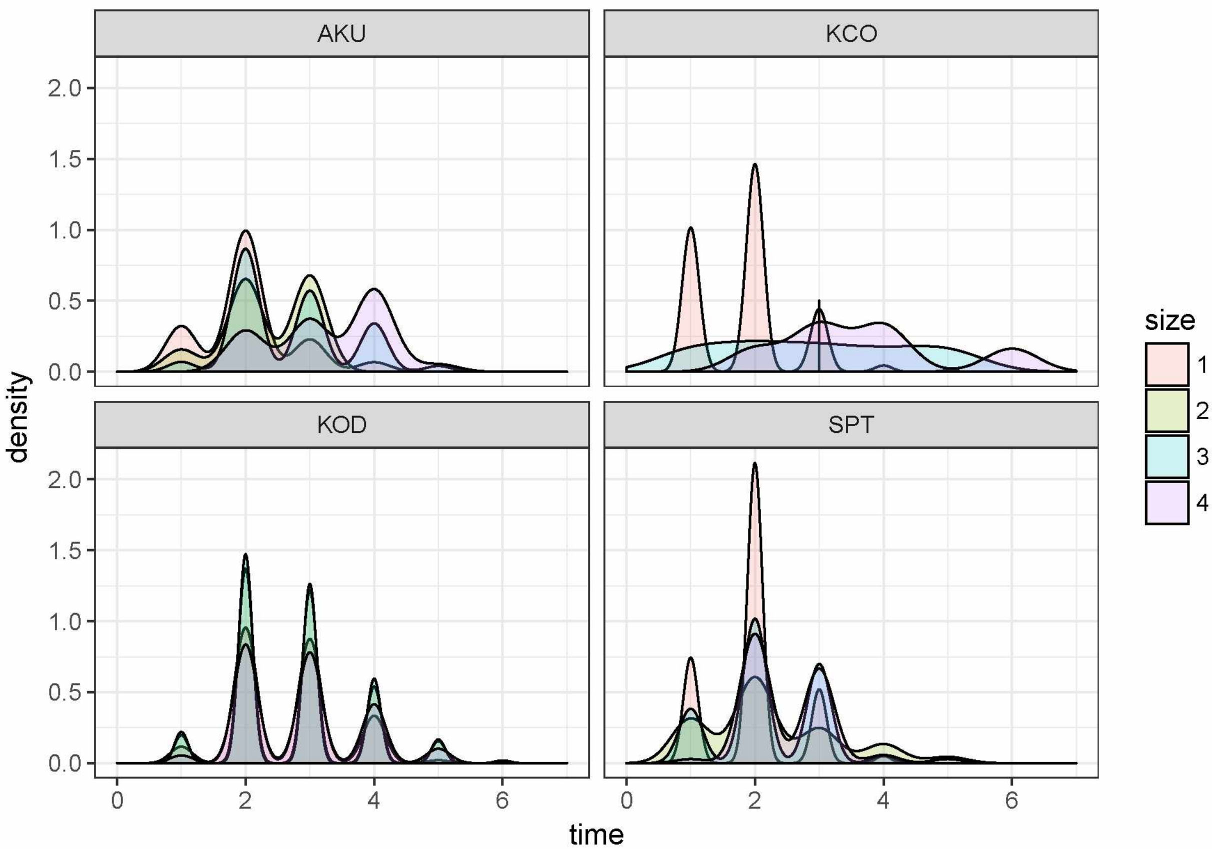

Figure C.2. Trip duration by vessel size, and port

Model results The model was tested using generalized input parameters from all years and compared to specific years. Each simulation was replicated 10 times for the years 2006, 2010 and 2014.

The TAC was set to the observed catch in the CFEC data - to avoid any discrepencies that may be present between the CFEC dataset and the NMFS catch accounting reports.

The function to determine TAC by year is:

```
tac.simcheck <- function(YEAR){
pol %>%
dplyr::select(year, p_fshy, port, season, p_holder, ton, area) %>%
group_by(port, season, p_holder, year) %>%
mutate(t = sum(ton) / n()) %>%
group_by(season, port, p_holder) %>%
mutate(tt = sum(t)) %>%
filter(tt>1) %>%
filter(year==YEAR) %>%
group_by(season, area) %>%
summarise(abc = sum(ton)) %>%
mutate(days = ifelse(season==1,51,
ifelse(season==2, 83,
ifelse(season==3, 38,32))), sim = 1) %>%
dplyr::select(area, season, days, sim, abc)  %>%
mutate(C1 = ifelse(area==1, abc, NA),
C2 = ifelse(area==2, abc, NA),
C3 = ifelse(area==3, abc, NA)) -> temp

# condense the data.frame
temp %>%
filter(C1>0) -> tac
tac$C2 = filter(temp, C2>0)$C2
tac$C3 = filter(temp, C3>0)$C3
tac %>%
dplyr::select(-area) %>%
mutate(C1 = C1,
C2 = C2,
```

```
C3 = C3) -> tac

tac %>%
left_join(f.boats()) %>%
left_join(f.trip_behavior()) %>%
filter(sim <11) %>%
mutate(deli = port, area = if_else(port==1, 1, 3)) %>%
dplyr::select(p_holder, p_fshy, area, port, deli, season, days=tday, t,
sd.t, day, sd.day, sim, C1, C2, C3, prob)
```

The simulation model functions are imported and the fuel and exvessel price state parameters are defined.

```
source('chapter_3/code/functions/model.R')

# Define world ----
fuel_price = 0.80 # set fuel price
ex1 <- ex2 <- ex3 <- ex4 <- 0.10 # set ex-vessel
```

The 2006 simulation was examined and replicated 10 times.

The observed and predicted results are reasonably similar for the type of model comparisons desired.

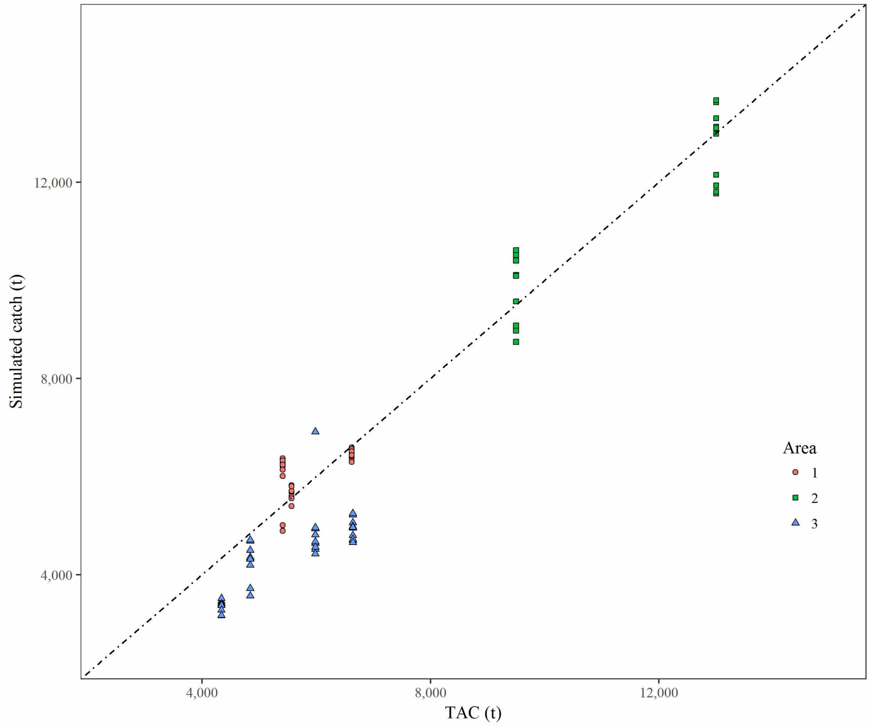

Figure C.3. 2006 simulation results based upon 2006 - 2014 input variables. The diagonal black line is a 1:1 ratio (perfect fit). Each dot represents the harvest (t) caught in a specific area and delivered to a specific port.

The 2010 simulation check

The 2010 simulation results have a greater variance than the 2006 results, though the results are generally divided above and below the replacement line.

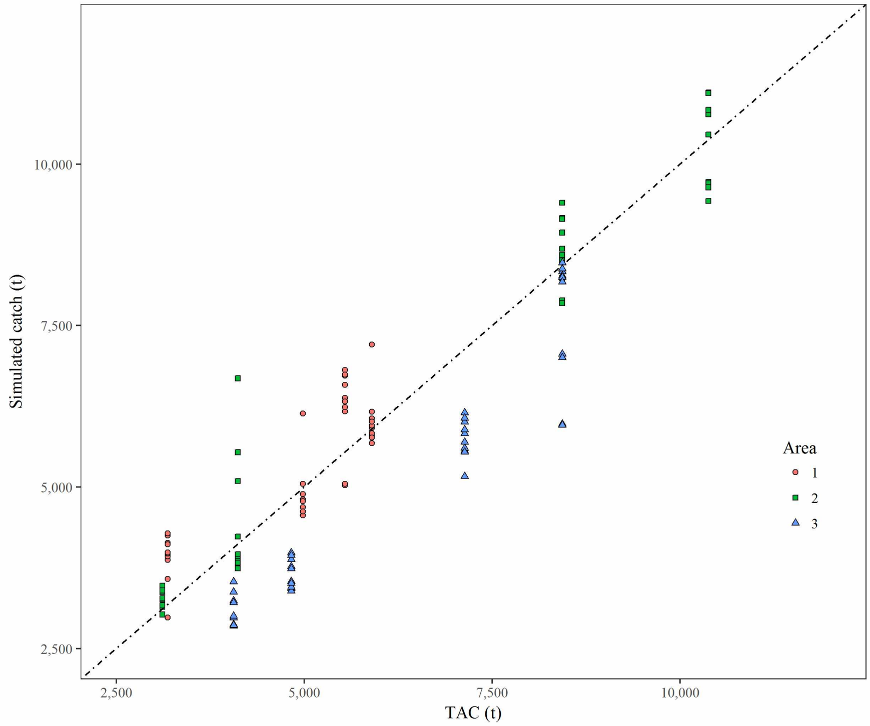

Figure C.4. 2010 simulation results based upon 2006 - 2014 input variables. The diagonal black line is a 1:1 ratio (perfect fit). Each dot represents the harvest (t) caught in a specific area and delivered to a specific port.

The 2014 simulation check

The 2014 simulation results show a fairly accurate simulation result to observed catch.

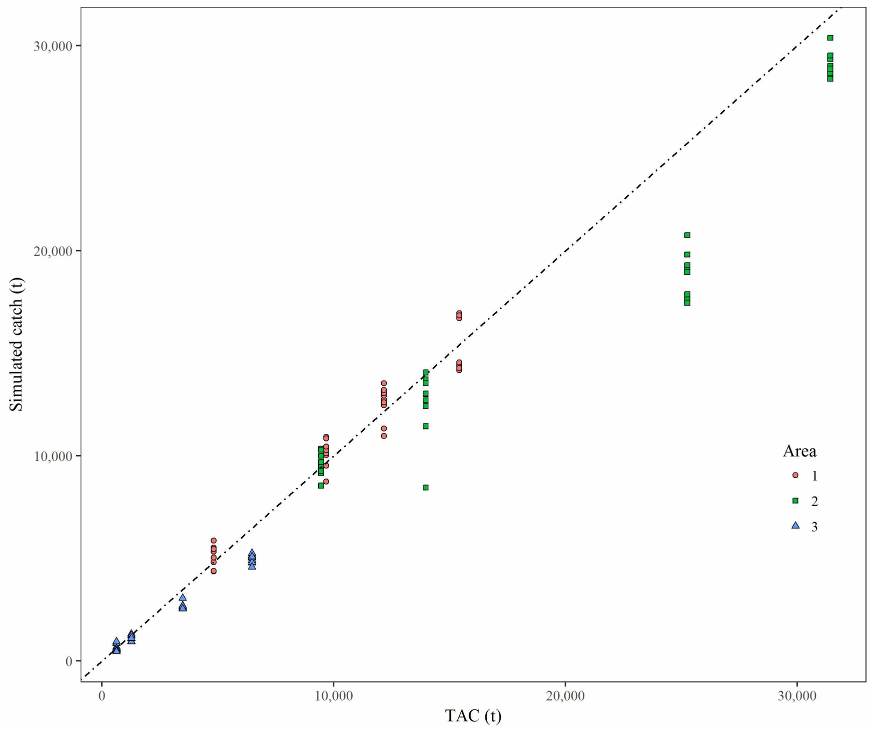

Figure C.5. 2014 simulation results based upon 2006 - 2014 input variables. The diagonal black line is a 1:1 ratio (perfect fit). Each dot represents the harvest (t) caught in a specific area and delivered to a specific port.

Appendix D
Model outputs

Model net revenue output for variable ABC inputs at various exvessel and fuel costs. At the top of each figure pane the number and letter designate the management scenario represented. The key to the federal numbers and state letters are found in Table D.1.

Table D.1. Management scenarios considered for simulation analysis.

Federal	State
1. IFQ	A. Open access
2. Catch-share community allocation	B. Limited entry
3. LLP w/ability to form cooperatives	C. Limited entry - super exclusive
4. Bycatch/prohibited species catch allocations	D. Limited entry - equal catch shares
SQ = Status quo	

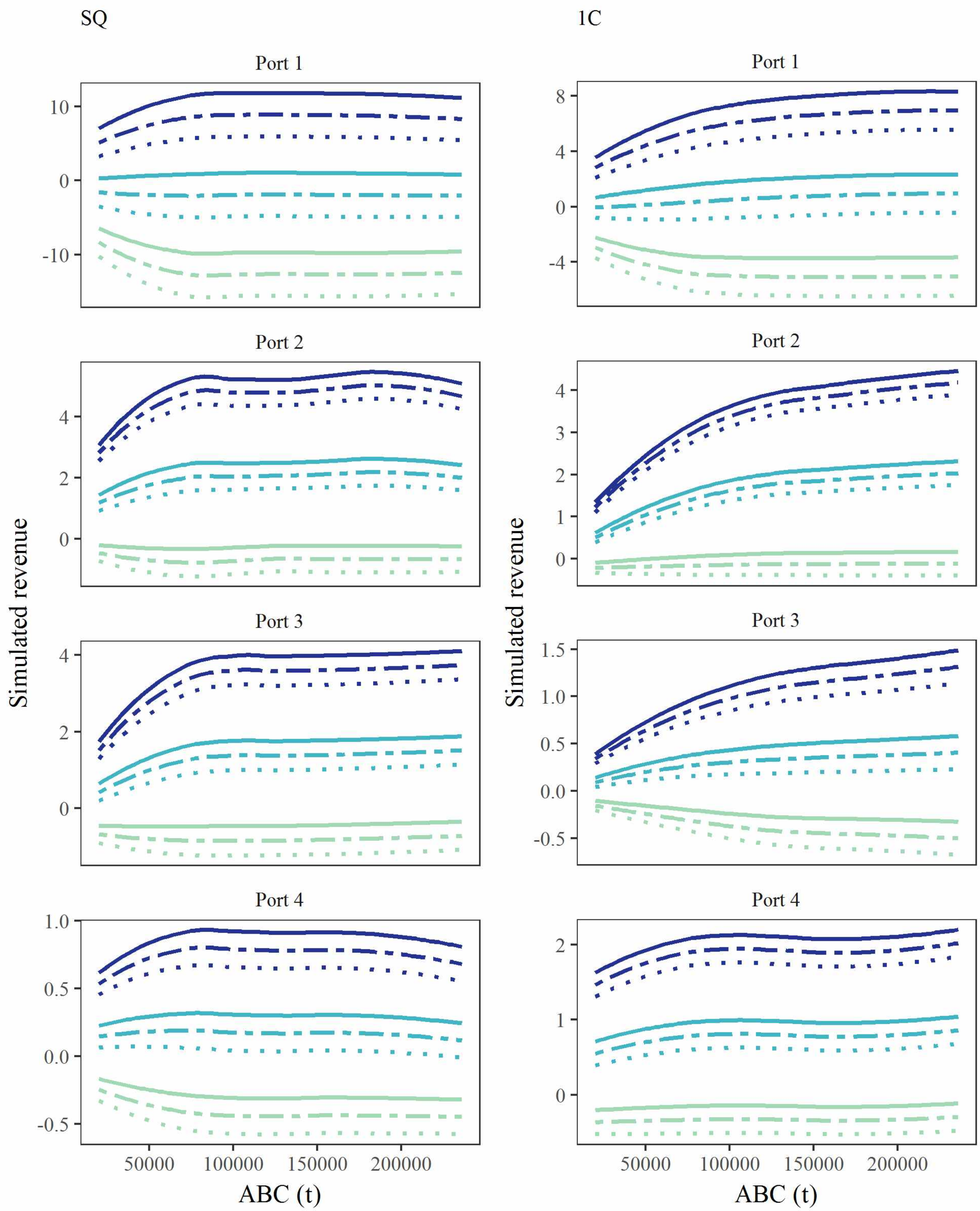

Figure D.1. Net revenue from Sequential ABC.

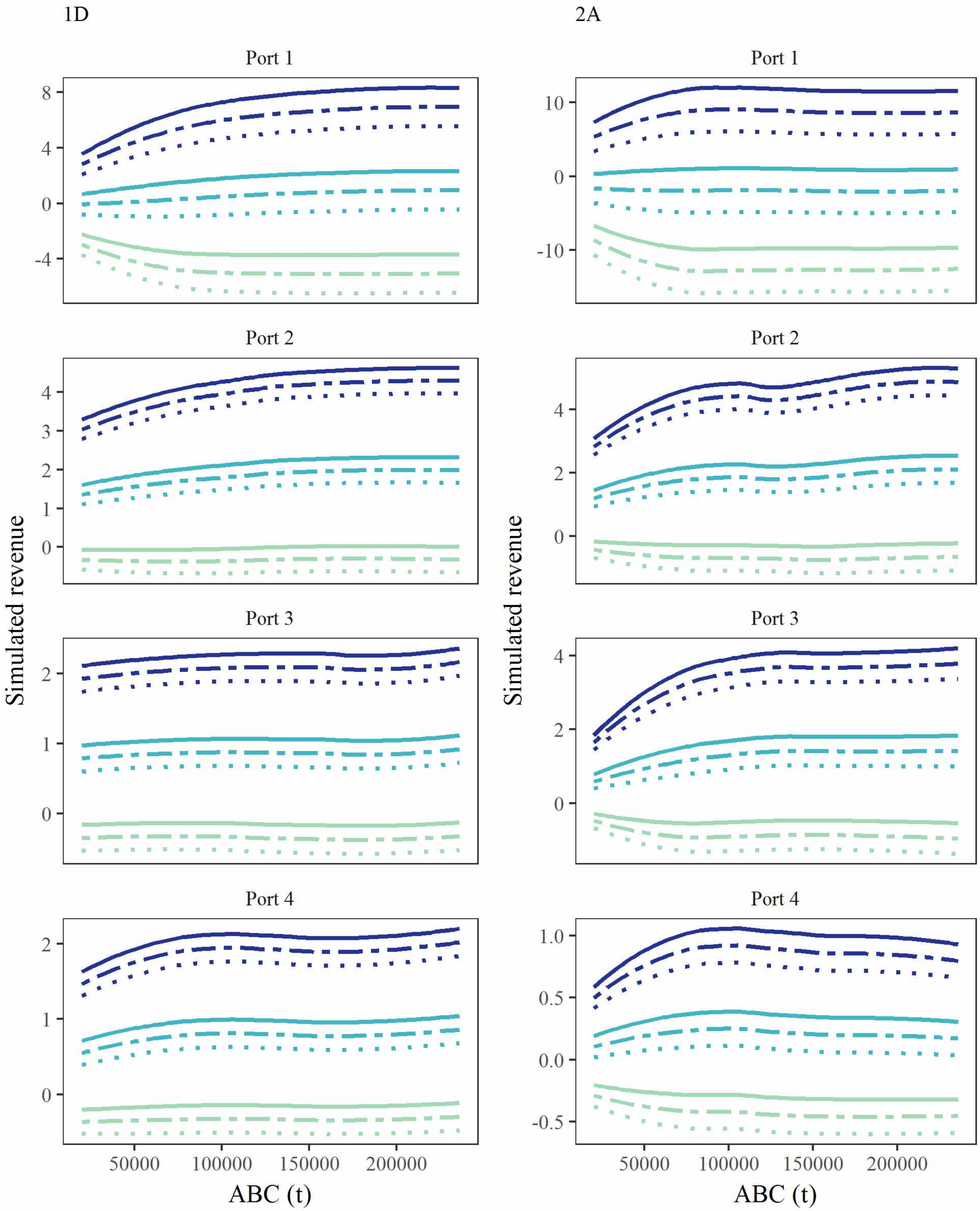

Figure D.2. Net revenue from Sequential ABC.

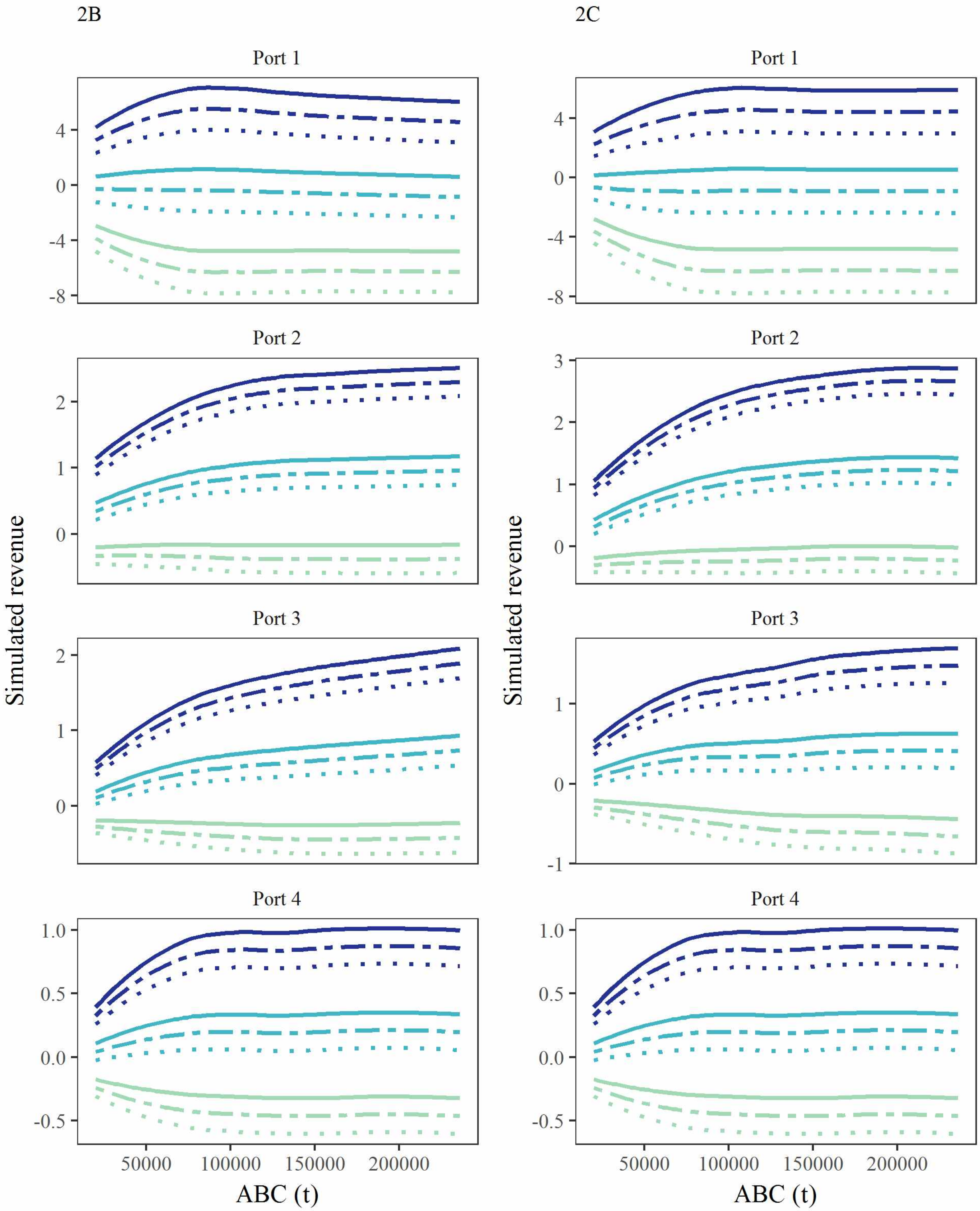

Figure D.3. Net revenue from Sequential ABC.

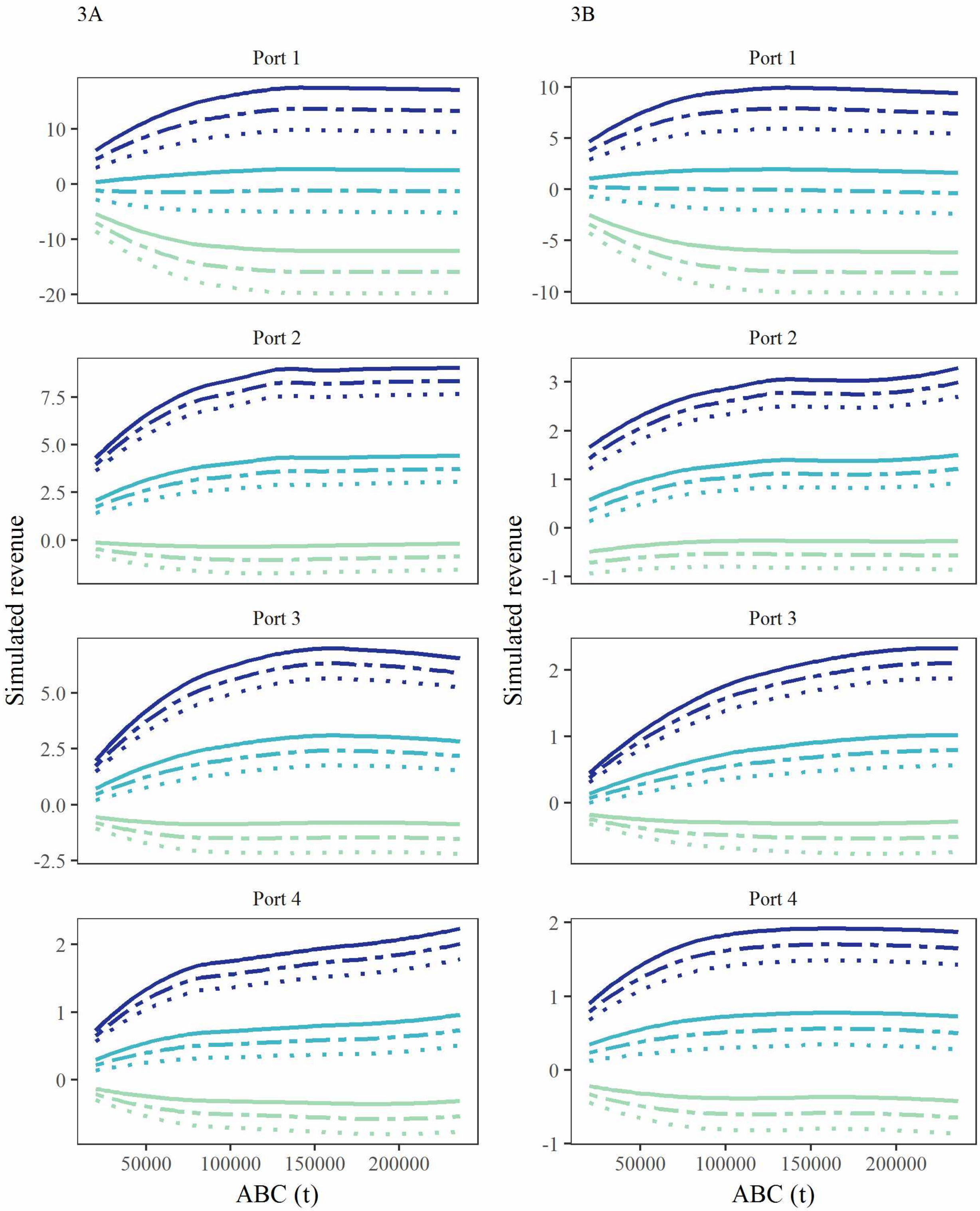

Figure D.4. Net revenue from Sequential ABC.

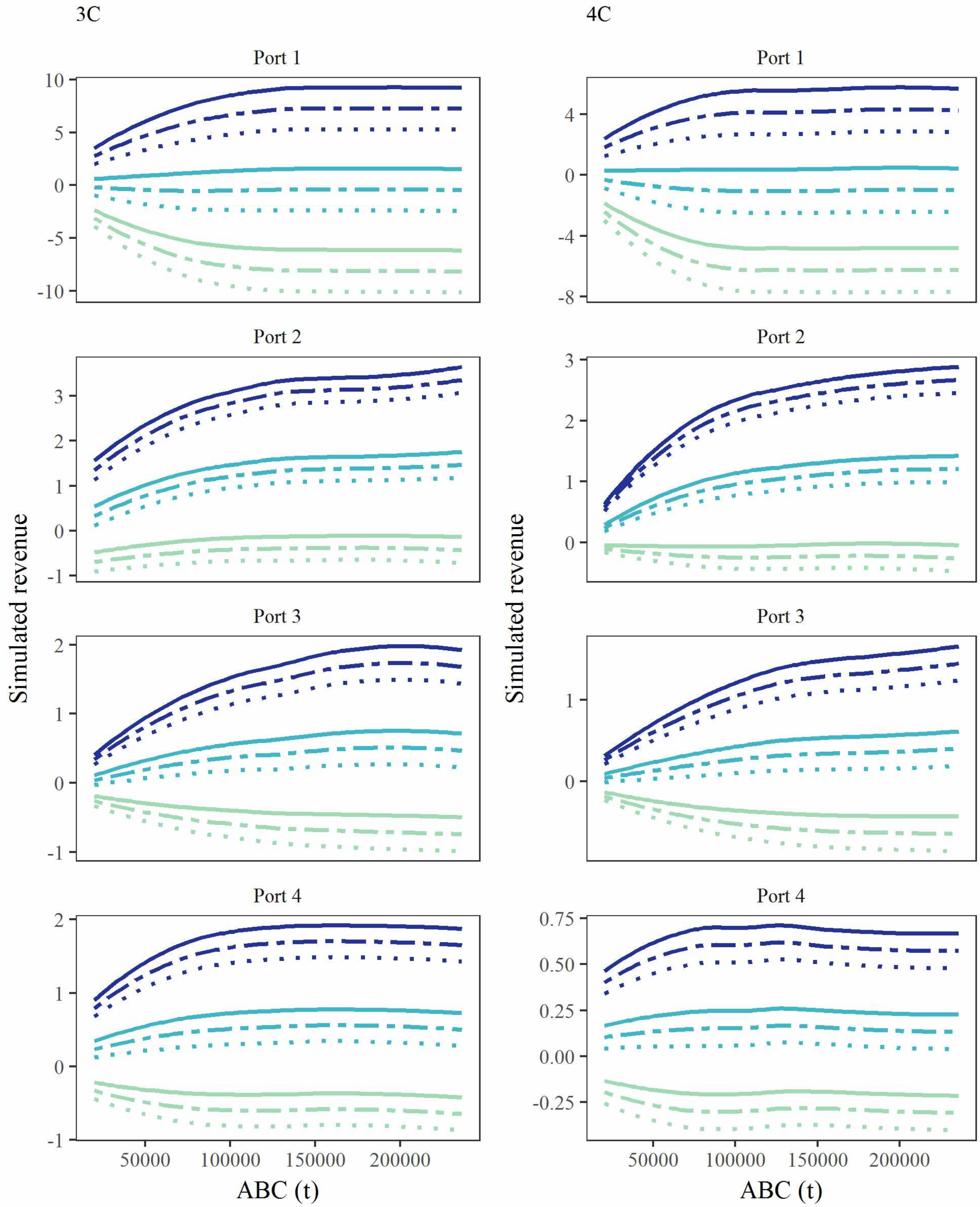

Figure D.5. Net revenue from Sequential ABC.

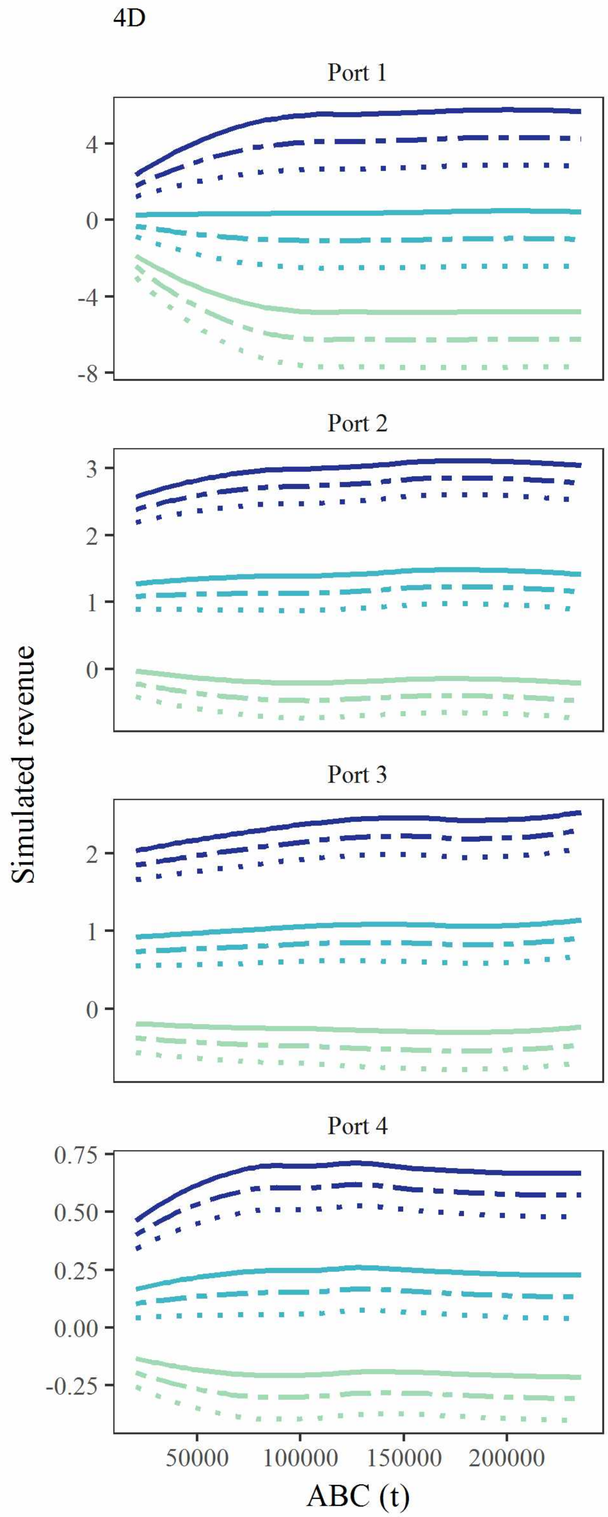

Figure D.6. Net revenue from Sequential ABC.